NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1393

A FLIGHT INVESTIGATION OF THE METEROLOGICAL CONDITIONS CONDUCIVE TO THE FORMATION OF ICE ON AIRPLANES

By William Lewis, U. S. Weather Bureau

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Moffett Field, Calif.

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The source of the subject report was inadvertently omitted from the cover and the first page of text. A revised copy of each, reading "By William Lewis, U. S. Weather Bureau," is attached.

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SUMMARY

Data from flight measurements of the meteorological factors related to the intensity of icing conditions are presented. The physical factors that establish the distribution of liquid water in clouds of various types are discussed and the results of the analysis are used to formulate certain rules for the forecasting of icing intensity. The problems of determining the range of values of the significant factors defining icing intensity for the purpose of the design of ice-protection equipment are discussed and tentative values are given.

INTRODUCTION

Over a period of several years, the NACA has conducted research on the prevention of ice formations on aircraft through the use of heat. Satisfactory wing, tail-surface, and windshield thermal ice-prevention systems were designed, fabricated, and tested in natural icing conditions for the Lockheed 12-A, Consolidated B-24, Boeing B-17, and Curtiss-Wright C-46 airplanes. (See references 1, 2, 3, and 4, respectively.) Each design was based on establishing, for clear-air conditions, a surface temperature rise which experience had shown to

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be adequate for ice prevention in simulated and natural icing conditions.

The NACA at present is engaged in an investigation to provide a fundamental understanding of the process of thermal ice-prevention in order (1) to establish a basis for the extrapolation of present limited test data to higher speeds and various shapes, (2) to provide data for improving the efficiency of thermal ice-prevention equipment, and (3) to provide a wet-air or meteorological basis for the preparation of design specifications for thermal ice-prevention equipment. The research consists of an investigation of the meteorological factors conducive to icing, and a study of the heat-transfer processes which govern the operation of thermal ice-prevention equipment for airfoils and for windshield configurations.

The meteorological phase of this investigation consists of the development of instruments required for the evaluation of the critical factors responsible for ice formation, and the actual measurement of these factors during flight in icing conditions. These measurements will furnish data establishing, for the pertinent meteorological variables, the range of values commonly encountered in icing conditions. These data are required as a basis for the definition of the physical characteristics of the maximum icing condition, for which ice-prevention equipment will be expected to provide adequate protection. As a result of this investigation, some progress is also being made toward a solution of the problems associated with the forecasting of icing conditions.

Previous results of this research program have been presented in references 5, 6, and 7. Reference 5 describes the first measurements in this investigation of the free water content of clouds. These were made by the dew-point method. References 6 and 7 deal with the meteorological aspects of icing conditions in stratus clouds and in precipitation areas of the warm-front type.

Research on the meteorological aspects of icing also has been conducted by various other agencies. Reference 8 presents the results of research in the development of thermal de-icing sponsored by the Air Materiel Command of the Army Air Forces. The Mount Washington Observatory, N. H., has been engaged for a number of years in a program of regular observations of icing conditions. The results of these observations and various articles and comments on icing measurement and related topics

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In continuation of this work, the C-46 airplane was equipped with special meteorological and electrically heated test apparatus, and flown in natural-icing conditions during the winter of 1945-46. Flight tests were conducted mainly along airline routes between the cities of San Francisco, Calif., Portland, Oreg., and Denver, Colo.

The purpose of this report is to present the meteorological results of the 1945-46 winter operations. The methods of observation and results obtained are presented first followed by a discussion of the progress made thus far toward a solution of the two major meteorological problems relating to icing conditions; namely, the problem of forecasting the intensity of icing conditions and the problem of defining the physical characteristics of the maximum icing conditions for which ice-prevention equipment will be expected to provide adequate protection.

Appreciation is extended to the Army Air Forces, the U.S. Weather Bureau, and United Air Lines, Inc. for their active cooperation in the research program. In particular, the services of United Air Lines Captain Carl M. Christenson, who served as pilot of the test airplane, contributed materially to the investigation.

APPARATUS AND METHOD

In the investigation of the physical properties of icing conditions it is desirable to measure the following quantities: (1) free-air temperature, (2) liquid water content, (3) average drop diameter, (4) distribution of drop diameters, and (5) concentration of ice particles. Completely satisfactory methods of measuring those quantities have not yet been developed. Sufficient progress has been made, however, to yield results which are very useful in the meteorological analysis of icing conditions. The methods used to measure the various quantities are described in the following paragraphs.

Free-Air Temperature

Free-air temperature was measured by means of a copper-constantan thermocouple connected to a millivoltmeter. The exposed junction of the thermocouple was baffled to prevent ice formation on the junction and shielded to protect against radiation errors. The installation on the airplane is shown in figure 1. The thermometer was subject to kinetic heating due to the speed of the airplane. A discussion of the corrections applied to the observed temperature measurements to obtain the true temperature of the undisturbed air will be found in the appendix of this report.

Liquid Water Content

The rotating-cylinder method of measuring liquid water content is generally regarded as being the most accurate and dependable procedure thus far developed. (See reference 8.) A full discussion of this method is given in reference 11. Most of the rotating-cylinder observations reported herein were made with the manually rotated assembly, consisting of two cylinders 1/8 and 1 inch in diameter, shown in figure 2. Shortly before the end of the investigation, the mechanically rotated assembly shown in figure 3 was installed. This apparatus consisted of four cylinders 1/8, 1/2, 1-1/4, and 3 inches in diameter. A discussion of the accuracy of the water-content data obtained by the rotating-cylinder technique is included in the appendix.

Drop Size and Drop-Size Distribution

The quantities involving drop size which are of most importance in the study of icing condition are the "mean-effective diameter," the maximum diameter, and the approximate volume distribution of diameter. The mean-effective diameter, which is approximately the average diameter, obtained by weighting the drops according to their volume, and the volume distribution of diameter are defined in the discussion of the rotating-cylinder method appearing in the appendix.

<u>Rotating-cylinder method</u>.- The rotating-cylinder equipment described above in connection with the measurement of water content provides data also on mean-effective diameter and drop-size distribution. The two-cylinder data furnish values of mean-effective drop diameter when certain assumptions concerning the size distribution are made. The four-cylinder data give some information on size distribution as well as mean-effective diameter. A further discussion of the rotating-cylinder method and an estimate of the accuracy of the results is included in the appendix. The methods of calculation are presented in reference 11.

<u>Area of catch method</u>.- The diameters of the largest drops present in significant quantity were determined from the width of the area of impingement of drops on a 4-inch nonrotating cylinder which is shown in figure 4. This cylinder was covered with blueprint paper and exposed briefly with its axis at right angles to the air stream. The methods of using the device and calculating the maximum diameter from the area of impingement were as described in reference 6, except that the data presented herein were calculated from the theoretical data presented in reference 11.

Concentration of Ice Particles

Satisfactory measurements of the ice crystal content of the air have not been made. This quantity has a negligible effect upon the rate of ice formation on unheated surfaces but may be of importance in determining the heat transfer from heated surfaces.

RESULTS

The significant characteristics of the various icing conditions encountered during the winter are summarized in table I. Each entry represents a weather situation which was fairly homogeneous as a whole although the minute-by-minute record may have indicated wide variations. For example, icing condition 19, table I, includes all data obtained during flight 33, although the flight was conducted in and out of scattered cumulus and cumulonimbus clouds in which the conditions were highly variable. The average water content shown is the unweighted mean of the individual measurements and, of course, does not include the time during which the airplane was flying in clear air between the clouds. Minimum values of water content were not included, since no attempt was made to measure the lowest values encountered. The maximum and minimum of altitude and temperature given in the table are the extremes encountered during the corresponding time intervals. Data are included in table I for nearly all the operations in clouds or precipitation, although in some cases little or no icing was experienced. In the case of flight 38, icing condition 24 represents conditions encountered in clouds composed predominately of water drops, while icing condition 25 represents conditions in clouds containing mostly ice crystals. These conditions both cover the same time interval, since both kinds of clouds were encountered from time to time throughout the period.

With the exception of icing conditions 1 to 4, inclusive, the values of liquid water content and drop size listed in table I were obtained by the rotating-cylinder method. In icing conditions 1 to 4, the liquid water calculations were based on photographs of the formations of ice collected on a stationary rod 0.5 centimeter in diameter, which was exposed in the air stream for periods of 1 minute.

A total of 232 observations of liquid water content and mean-effective drop diameter were made by the rotating-cylinder method during icing conditions 5 to 42, inclusive. As these are the most reliable measurements available from this investigation, they have been used as the basis for a study of the relation of icing conditions to cloud forms. For the purpose of this study, cloud forms have been divided into two general types: "layer clouds" and "cumulus clouds," as defined hereinafter. The pairs of corresponding values of liquid water content and mean-effective drop diameter have been divided into four groups corresponding to the following conditions: (1) layer clouds without ice particles, (2) layer clouds with ice particles, (3) cumulus clouds without ice particles, and (4) cumulus clouds with ice particles. These data have been plotted in several ways in order to study any relationships which may exist between the various quantities.

In figure 5, values of liquid water content have been plotted against mean-effective drop diameter; figures 6 and 7 present liquid water content and drop size versus pressure altitude; and figure 8 and 9 show liquid water content and drop size versus temperature.

Comments on the Data in Table I

Icing conditions 2 and 3, table I, which were observed on the same day over the same area, illustrate the effect of the change of air-mass characteristics and flow patterns accompanying the passage of a cold front. The extensive prefrontal cloud formation of icing condition 2 was composed almost entirely of ice particles and produced only a trace of icing, while the scattered cumulus clouds in the unstable postfrontal air mass of icing condition 3 contained as much as 1.4 grams of liquid water per cubic meter which caused very rapid ice formation.

Icing contions 26 and 31, which occurred in upslope stratus clouds over southern Wyoming, are examples of continuous icing conditions covering a large area in which flight of considerable duration might be required. The liquid water content in these conditions averaged about 0.3 and 0.4 gram per cubic meter, respectively, during a period of over 2 hours in each case.

Icing condition 28 is noteworthy because of the high altitude and low temperature. The greatest liquid water content measured on this flight was 1.1 grams per cubic meter, which occurred at a pressure altitude of 17,000 feet and a temperature of -3° F. Low-temperature icing conditions of this kind give rise to the most serious icing of propellers, since the effect of kinetic heating is insufficient to prevent the formation of ice, even at the high speed of the blade tips. Severe propeller ice was also observed in icing condition 11, during which the liquid water content reached 0.5 gram per cubic meter at a temperature of -6° F.

The largest value of mean-effective drop diameter, 50 microns, was measured in icing condition 34. Although the corresponding water content was quite low, 0.15 gram per cubic meter, this condition caused servere icing on the C-46 windshield, which, because of its flush configuration, is not susceptible to icing except when large drops are present.

The highest value of liquid water content encountered during the season was measured in icing condition 39. This occurred in a large cumulus congestus cloud just as the transformation to cumulonimbus began. The rapidly changing conditions observed in this cloud are shown in table II and discussed in detail later in this report.

The Classification of Icing Clouds

An examination of the data in table I reveals that all the icing conditions with values of liquid water content of 0.8 gram per cubic meter or more occurred in cumulus clouds. For this reason it is convenient in the study of icing conditions to divide cloud forms into two general classes.

Layer clouds.— Stratus, stratocumulus, and altocumulus have been grouped together since they are all limited in vertical extent. At temperatures below freezing, continuous cloud layers composed of liquid drops are rarely more than 2000 to 3000 feet thick. Altostratus and nimbostratus have also been included as layer clouds. Although altostratus are sometimes several thousand feet in vertical extent, they are generally, during winter, composed almost entirely of ice crystals except for occasional thin layers and small patches containing water drops.

Cumulus clouds.— Cumulus humilis, cumulus congestus, cumulonimbus, and altocumulus castellatus are included in this category. Clouds of this type are formed by the ascent of individual parcels of air relative to the air mass as a whole. They frequently greatly exceed the layer-type clouds in vertical extent. The individual cloud masses are generally rather limited in horizontal extent and comprise only a minor fraction of the total air mass.

DISCUSSION

The Problem of Forecasting Icing Conditions

In the discussion which follows of the problem of forecasting icing conditions, this particular problem will be defined in relation to the general problem of weather forecasting. Weather Bureau definitions now in use of degrees of icing intensity will then be interpreted in terms of the fundamental physical quantities, liquid water content, and drop diameter, and not in terms of the accumulation of ice on aircraft, inasmuch as ice accumulations would vary widely for identical icing conditions, being dependent upon the type of aircraft and the nature of the ice-protection equipment. The factors determining the liquid water content of clouds will be considered next, followed by an examination of the problems relating to drop size. The results of theory and observation will then be summarized in the form of a series of tentative rules for estimating the intensity of icing conditions.

Formulation of the problem.— The problem of forecasting the occurrence and intensity of icing conditions is but a small part of the general problem of weather forecasting. For several years, meteorological and air-transport organizations have regularly prepared forecasts of weather conditions including the location, type, altitude, and extent of cloud masses and the occurrence and type of precipitation. The preparation of such forecasts is generally regarded as one of the most important problems of practical meteorology and a great deal of effort has been and is being directed toward the improvement and refinement of the techniques of forecasting.

For the purposes of this discussion of the problem of forecasting icing intensity, it will be assumed that satisfactory forecasts of the type, location, thickness, altitude and temperature of cloud masses, and the occurrence and type of precipitation can be made. It is realized fully that this assumption is frequently not valid. It is made here in order to separate the problems peculiar to forecasting icing intensity from the general problem of weather forecasting. In other words, the problem to be treated here is that of estimating the icing intensity to be expected within a cloud of known type, dimensions, and temperature. If this can be done satisfactorily, a forecast of icing intensity can be derived from any good forecast of weather and cloud conditions. Moreover, regardless of whether satisfactory forecasts of cloud conditions can be made, reliable estimates of the icing intensity present in the currently observed and reported cloud conditions may be of considerable value.

<u>The definition of icing intensity.</u>- It is now generally recognized that the principal factors determining the intensity of an icing condition are the concentration of supercooled liquid water and the diameter of the drops. In addition, when thermal methods of de-icing are considered, the air temperature and the amount of snow in the air have an important effect upon the heat requirements. Icing intensities have been defined by the U.S. Weather Bureau for reports from mountain stations in terms of the rate of collection, at 200 miles per hour on a 3-inch-diameter circular cylinder, expressed in grams per hour per square centimeter of projected area. (See reference 12.) The definitions are as follows:

Trace of ice	0 to 1.0 gram per square centimeter hour
Light ice	1.0 to 6.0 grams per square centimeter hour
Moderate ice	6.0 to 12.0 grams per square centimeter hour
Heavy ice	12.0 and over grams per square centimeter hour

The values of collection efficiency of cylinders given in reference 11 have been used to express the foregoing definitions of icing intensity in terms of liquid water content and uniform drop diameter at 10,000 feet pressure altitude and 15° F. The results are shown by the curves in figure 5. The effects of variations in pressure altitude and temperature are small and will be neglected. It should be noted that the curves defining icing intensity are based upon the assumption of uniform drop size, while the observational data, indicated by the plotted points in figure 5, are expressed in terms of mean-effective diameter. An examination of the data presented in reference 11 for various distributions of drop diameter reveals that, for the case of a 3-inch-diameter cylinder at 200 miles per hour and values of mean-effective drop diameter usually found in clouds, the differences in catch efficiency due to variations in drop-size distribution are small.

In the following discussion of the problem of estimating icing intensity, the factors determining the concentration of liquid water in clouds will be considered first and then the effect of drop size will be examined.

<u>Water content of clouds composed entirely of liquid drops</u>.- For the purpose of the study of the liquid water content of clouds, it is convenient to divide liquid clouds into two general classes according to the processes of their formation, namely: (1) clouds formed by turbulence and convection in air that is generally in unstable or neutral equilibrium, and (2) clouds formed by the lifting of large stable air masses by convergence or orographic or frontal action. It should be noted that portions of stable air masses may occasionally become unstable due to lifting, thus giving rise to the production of clouds of class (1) by local convection and turbulence.

The first class, which includes cumulus, stratocumulus and most types of altocumulus and stratus is characterized by approximately moist adiabatic lapse rate and nearly constant ratio of air to total water (liquid plus vapor) within a single cloud mass or layer as long as no precipitation occurs. The principles which determine the concentration of liquid water in clouds of this type may best be illustrated by the case of a simple convective cumulus cloud. Consider a parcel of air which is lifted adiabatically from the surface to an altitude of several thousand feet. For the purpose of this discussion it will be assumed that conditions in the air mass are suitable for the convection to take place. Suppose the mixing ratio at the surface is x_t grams of water vapor per kilogram of dry air. When the ascending parcel reaches the temperature and pressure at which x_t is the saturation mixing ratio, condensation takes place. As long as the cloud is composed entirely of liquid drops, these are almost always so small that their velocity of fall is negligible compared to the turbulent motions in convective clouds. Hence the drops are carried along with the air parcel in which they originated, thereby keeping the total water content, liquid plus vapor, per unit mass of air constant and equal to x_t, the initial mixing ratio. At any point within the cloud mass where the saturation mixing ratio is x_s, the liquid water content W_l is given by

$$W_l = (x_t - x_s)\,\rho$$

where ρ is the dry-air density. If x_t and x_s are expressed in grams per kilogram and ρ is in kilograms per cubic meter, W_l is given in grams per cubic meter.

An example of this type of cloud formation was observed in the vicinity of Cheyenne, Wyo., on Apr. 9, 1946 (icing condition 28, table I) when a cumulus cloud which reached an altitude of 20,000 feet was investigated. Most of the cloud had turned to snow but one portion at about 17,000 feet pressure altitude was found to be composed almost entirely of liquid water. Measurements within this portion of the cloud indicated a liquid water content of 1.1 grams per cubic meter at a temperature of -3° F. A comparison of the flight data with the theory of adiabatic lifting indicated close agreement. In figure 10, the temperature-pressure curve from observations in clear air outside the cloud is shown as a solid line. The dotted line represents the probable history of the ascending parcel forming the cloud. The observation within the liquid portion of the cloud is shown as a circle. The surface dew point as reported from Cheyenne was 21° F, which corresponds to a mixing ratio of 3.0 grams per kilogram. The saturation mixing ratio (with respect to liquid water) at 17,000 feet pressure altitude and -3° F is 1.5 grams per kilogram and the air density is 0.72 kilogram per cubic meter. Using the equation derived above, the liquid water content is

$$W_l = (3.0 - 1.5)\ 0.72 = 1.08 \text{ grams per cubic meter}$$

This close agreement with the measured value, though partly fortuitous, is a fairly good indication that the water content of that portion of the cloud had not been appreciably depleted by mixing or precipitation although the convection extended to a high altitude and very low temperature.

The method just described for calculating the liquid water content of cumulus clouds may be applied also to stratus and strato-cumulus clouds when these are formed by active mixing within the surface turbulence layer, since such mixing tends to produce a condition of constant total water mixing ratio and adiabatic lapse rate. Clouds of this kind have been discussed in reference 6 which includes curves giving the liquid water content in terms of the cloud-base temperature and the height above the cloud base for clouds formed adiabatically by convection or turbulence. Observations made during the 1945-46 season indicate that the observed values of water content reported in reference 6 were somewhat too high, since they were obtained by the dew-point method and are subject to sampling errors. It now appears that in clouds composed of liquid drops, the value of liquid water content calculated on the basis of adiabatic lifting from the cloud base is a practical upper limit which is unlikely to be significantly exceeded. The actual observed concentration of liquid water is generally somewhat lower than the calculated value. In layer clouds this difference is believed to be due to incomplete mixing of the moist air within the turbulent layer and some mixing downward of dry air from above, while in cumulus clouds it is probably due to mixing with the dry air through which the cloud is rising.

The second class of clouds previously mentioned, those which are formed by the lifting of stable air masses, includes altostratus, some types of altocumulus (such as lenticularious) and "upslope" stratus. In this case there is no simple method of estimating the liquid water content, since it depends largely upon the initial humidity distribution. Also, due to the lack of turbulence in clouds of this type, the velocity of fall of the drops with respect to the air may at times have a significant effect upon the water content.

Nearly all of the altostratus cloud systems encountered during this investigation were composed almost entirely of ice crystals, the only exception being icing condition 34, table I. It is believed that though altostratus clouds composed of liquid drops are infrequent in northern United States during winter, they might be encountered more frequently under warmer conditions. The values of liquid water content observed in icing condition 34 were generally less than would usually be encountered in stratocumulus clouds of the same temperature and vertical extent.

The limited experience obtained in the investigation of two cases of upslope stratus (icing conditions 26 and 31, table I) suggests that the water content of such clouds is much less than would be derived from the assumption of adiabatic lifting from the cloud-base level.

Due to the very limited amount of data available for situations of this type, it is not possible to state conclusively at this time whether values of liquid water content greater than those based on adiabatic lifting might not sometimes be encountered in clouds formed by the forced ascent of stable air masses. It is believed, however, on the basis of such observations as have been made, that the values of liquid water content calculated on the basis of adiabatic lifting from the cloud base represent a practical upper limit which is unlikely to be significantly exceeded in clouds of any type, at temperatures below freezing.

The liquid water content of clouds containing snowflakes.- The general problem of the coexistence of liquid water drops and ice crystals in clouds has been treated in reference 9. It has been shown that liquid water drops of the size usually found in clouds evaporate very quickly in an atmosphere saturated with respect to ice at below freezing temperatures. Similarly, ice crystals grow rapidly in an atmosphere saturated with respect to liquid drops. A mixture of ice crystals and liquid water drops below 30° F is thus a very unstable condition and must be regarded in general as only a transient stage in the evolution of cloud forms.

In this discussion, the terms "ice crystals," "snowflakes," and "precipitation" are used interchangeably. This is justifiable since any ice crystals large enough to be observed as discrete particles from an airplane in flight are many times larger than cloud drops and thus have an appreciable rate of fall although they may evaporate before reaching the ground.

Three cases of interaction of snow and liquid water should be recognized. First, the condition within a layer cloud composed mainly of liquid drops when scattered snowflakes are present; second, conditions necessary for the existence of liquid drops with a high concentration of snowflakes; and third, the sudden transformation of a cumulus cloud into cumulonimbus which occurs when ice particles form in the upper portions.

In the first case, the snowflakes may form within the cloud layer or may fall into it from above. The depletion of liquid water caused by the formation of snowflakes within a cloud layer has been discussed in reference 6. When snowflakes fall from above into a liquid water cloud, as for example when a precipitating altostratus cloud overlies a stratocumulus layer composed of water drops, the rate of depletion of liquid water depends chiefly upon the concentration of snowflakes. With the rates of snowfall which usually occur from the altostratus clouds associated with low-pressure areas, the drying up of a stratocumulus layer proceeds quite rapidly.

The second case mentioned previously, the situation in which many snowflakes are present, has been treated in reference 7, in which it is shown that stable, precipitating, warm-front-type cloud systems do not, in general, contain liquid water drops at below-freezing temperatures except in the immediate vicinity of the freezing level. Experience during the 1945-46 season indicates that the discussion given therein applies in general to the altostratus-nimbostratus cloud system associated with cyclonic storms even though the frontal structure may be confused and indefinite.

In the third case, the formation of ice crystals within a cumulus cloud may result in a very rapid depletion of the liquid water content. An example of this process was observed (icing condition 39, table I) when a large well-developed cumulus cloud was investigated by means of observations during four successive runs through the cloud. A record of these observations is given in table II.

As the cloud was approached for the first run, it had the appearance of a typical cumulus congestus cloud without any visible softening of outlines in the upper portions. Since scattered snow pellets were observed during the first run in the cloud, it is believed that precipitation had just begun at that time. During the succeeding 18 minutes, the liquid water content within the cloud diminished from 1.9 to 0.2 grams per cubic meter as a result of the sudden formation and rapid growth of solid precipitation particles. After the last run, the cloud was observed to have the form and appearance of a typical cumulonimbus with a definite anvil top and soft outlines throughout the upper part. Unfortunately, the observations recorded in table II were not all made at the same altitude, hence part of the observed variation in cloud composition may have been due to differences of altitude. Nevertheless, the complete change in appearance of the cloud during the period of the observations supports the interpretation given here that the observed changes were real changes with time of the characteristics of the entire upper portion of the cloud.

The dynamic effects of such a rapid transformation from cumulus congestus to cumulonimbus are worthy of note. The temperature rise caused by the liberated heat of fusion combines with the simultaneous removal of water by precipitation to produce a sudden decrease in density of the cloud mass, which in the case under discussion was calculated to be about 0.4 percent. This effect may help to account for the violent conditions often observed in cumulonimbus clouds. A detailed treatment of the dynamics and thermodynamics of cumulonimbus clouds is contained in reference 13.

<u>Observational checks of water-content theory</u>.- The observations made during the winter of 1945-46 cannot be used directly to check the foregoing theories concerning liquid water content, since the altitude of the cloud base was usually unknown during the measurements. Certain deductions from the theory can be checked against the data, however. For example, since layer clouds are generally limited in depth to 2000 or 3000 feet, while cumulus clouds may have a much greater vertical extent, the liquid water content

observed in layer clouds would be expected to have a definite upper limit, while much higher values would be observed in cumulus clouds. The effect of precipitation in lowering the liquid water content would be expected to increase the frequency of low values and lower the maximum liquid water content for both types of clouds.

Figure 11, which is based on the data of figure 5, shows the frequency of occurrence of various values of liquid water concentration for cumulus clouds and layer clouds, with and without precipitation. The deductions given above are verified except for the rather high frequency of large amounts of liquid water in cumulus clouds with precipitation. This is probably due to the fact that as cumulus clouds become taller they are more likely to contain precipitation, hence on the average the observations in cumuli with precipitation were made in larger and more fully developed clouds.

In conclusion, the principles discussed above which determine the liquid water content in clouds provide a means of estimating, with reasonable accuracy, the maximum liquid water content to be expected in the subfreezing portion of a cloud system of known type, dimensions, and temperature.

The problem of drop size.- In order to express an estimate of maximum liquid water content in terms of icing intensity, it is necessary to consider the problem of estimating the drop diameter and its effect upon the intensity of icing.

The data presented in figures 5, 7, and 9 have been examined to determine what relationship, if any, exists between the mean-effective drop diameter and the liquid water content, cloud type, temperature, and altitude. The most obvious characteristic of all of these diagrams is the lack of any clear-cut patterns which would indicate reliable correlations among the various quantities. Some important information can be obtained from these data, however, especially on the relationship between cloud type and the range of values of liquid water content and mean-effective diameter. An examination of the data presented in figure 5 discloses a relation between water content and the observed range of values of mean-effective diameter. For values of liquid water content below 0.2 gram per cubic meter, the range of mean-effective drop diameter is from 5 microns or less to 45 microns or more for both cloud types. As the water content increases, the range of drop diameter decreases for both types. Of a total of 32 observations in cumulus clouds containing 0.7 or more grams of liquid water per cubic meter, all the values of mean-effective drop diameter were included in the range from 10 to 23 microns. Of a total of 30 measurements in layer clouds with a water content of 0.4 gram per cubic meter or more, all have mean-effective diameters in the range from 9 to 20 microns. It is also noted that the value of mean-effective diameter corresponding to the highest liquid water content is 17 microns for cumulus clouds and 11 microns for layer clouds.

The determination of icing intensity from cloud type and estimated liquid water content.- Since it is not possible, on the basis of present knowledge, to estimate the drop size to be expected in a cloud, and since fairly good estimates of maximum liquid water content can be made, the question arises as to whether reasonable estimates of maximum icing intensity are possible. If such estimates are to be made they must be based upon liquid water content and cloud type alone. It is proposed, therefore, in the absence of more complete knowledge of drop sizes, to select a value of drop diameter to be assigned to each major cloud type, and to estimate the icing intensity on the basis of this arbitrary diameter and the expected liquid water content. Values of assumed diameter of 14 and 17 microns have been chosen for layer clouds and cumulus clouds, respectively. These values were chosen on the basis of a careful examination of the data of figure 5, consideration being given to the fact that an estimate of higher than actual icing intensity is less objectionable from a forecasting standpoint than too mild an estimate.

This choice of assumed values of drop size determines the range of values of liquid water content to be associated with each degree of icing intensity as indicated by the curves in figure 5. In other words, this procedure amounts to setting up an alternate scale of icing intensity based upon liquid water content alone and differing slightly for the two classes of clouds. In order to check the degree of agreement between these alternate scales and the scale defined by the curves in figure 5 over the observed range of liquid water content and drop size, the observational data of figure 5 have been arranged in the following table:

Cloud type	Range of water content	Number of observed cases of icing of various intensities				
		Alternate scale of icing intensity (determined by assumed diameter)	Weather bureau scale of icing intensity			
			Trace	Light	Moderate	Heavy
Layer clouds assumed diameter, 14 microns	0 – 0.11	Trace	34	4	0	0
	0.12–0.68	Light	15	72	1	0
	0.69–1.33	Moderate	0	0	0	0
	over 1.33	Heavy	0	0	0	0
Cumulus clouds assumed diameter, 17 microns	0 – 0.07	Trace	4	1	0	0
	0.08–0.49	Light	7	35	3	0
	0.50–1.00	Moderate	1	15	23	3
	over 1.00	Heavy	0	0	2	12

The data in the table show that out of 232 cases the two scales agree for 180 cases (78 percent), and that the alternate definition indicates a higher icing intensity in 40 cases (17 percent) and lower intensity in 12 cases (5 percent).

It should be noted that the data of figure 5 which were used to choose the assumed values of drop size were also used to verify the validity of the results. If these data do not constitute a representative sample, the degree of agreement indicated will not be attained in general.

It is fully realized that more accurate and dependable estimates of the intensity of icing conditions could be made if the drop size could be predicted, and therefore that the development of methods of predicting drop sizes is desirable. Until such methods are discovered, however, the method proposed herein for estimating icing intensity on the basis of an intensity scale based on arbitrarily assumed values of drop size offers to meteorologists a practical and fairly reliable means of dealing with the problem of forecasting the intensity of icing conditions.

The foregoing discussion has been based on the scale of icing intensity defined by the Weather Bureau in reference 12. This type of definition is probably as good as can be devised as a scale to be used for general purposes in the dispatching of aircraft and reporting of conditions encountered in ordinary operations. It is believed, however, that the average pilot's or meteorologist's concept of "moderate" or "heavy" icing is considerably milder than indicated by this scale. In fact, this scale would probably be in better agreement with the average pilot's estimate of icing intensity if the terms "trace," "light," "moderate," and "heavy" were replaced by "light," "moderate," "heavy," and "very heavy," respectively.

No simple scale of light, moderate, and heavy icing is adequate for engineering purposes. Values of liquid water content, mean-effective drop diameter, maximum drop diameter, and temperature must all be taken into account if an icing condition is to be adequately described from an engineering standpoint

Some tentative rules for estimating the intensity of icing conditions.- The foregoing discussion suggests several rules for estimating icing intensity. Although these generalizations are based on a limited number of measurements which may not have been representative of all conditions, they are supported by a considerable amount of qualatative observational experience and have a sound physical basis. Moreover, the observations were made over a large geographical area including wide variations in climate and topography, and included investigations of conditions in a wide variety of synoptic situations

The dependence of icing intensity upon cloud type and the presence or absence of precipitation is illustrated by figure 12, which shows the percentage of observation of each degree of icing intensity for layer clouds and cumulus clouds, with and without precipitation. It should be pointed out in connection with figure 12, that the data presented therein, like all the data in this report, are likely to be biased by the inclusion of an unduly high percentage of observations in the more severe conditions. This is the result of the practice, which was followed throughout the flight program, of attempting to fly at all times in the most severe icing conditions available and remaining in such conditions as long as practicable. Another practice, which gives a similar bias to the data, was the habit of making the observations more frequently in the heavier icing conditions.

The relationships apparent in figure 12 and the general principles determining the liquid water content of clouds have been used to formulate the following tentative rules for estimating the intensity of icing conditions according to the intensity scale given in reference 12:

1. In layer clouds with precipitation, icing intensities greater than a trace are unlikely except near the edges of the precipitation areas or where the precipitation is very light or has just begun.

2. In clouds formed by convection or turbulence the icing intensity usually varies with temperature and height above the cloud base as indicated by the theory for adiabatic lifting, but the actual water content is usually less than the calculated value.

3. In layer clouds without precipitation, icing conditions are usually light but are occasionally moderate near the tops of thick layers.

4. Moderate and heavy icing conditions usually occur only in cumulus clouds, but conditions in the upper portions of unusually thick stratus or stratocumulus layers occasionally reach moderate intensity.

5. Icing conditions in cumulus clouds are highly variable and in the upper portions of tall clouds may be very severe.

6. During winter, heavy icing conditions are not likely to be encountered continuously for more than 2 to 3 minutes.

The Problem of Defining the Physical Characteristics of Icing Conditions for the Purpose of the Design of Ice-Protection Equipment

The second major problem in this investigation is that of defining the significant properties of the most severe icing conditions likely to be encountered in the course of all-weather transport operations in a given area during a particular season. The following remarks refer to conditions in the northern half of the United States during winter except when other areas or seasons are specifically mentioned, as for example in the discussion of summer cumulus clouds.

Maximum icing conditions in cumulus clouds.- It is seen by reference to figure 5 that the heaviest icing conditions observed in cumulus clouds are much more severe than any experienced in layer clouds. It follows therefore that the heaviest possible icing condition, chosen without regard to its extent or duration, may be expected to occur in cumulus clouds. As mentioned in the preceding section, the maximum liquid water content within the subfreezing portion of a cumulus cloud may be determined by calculating the free water produced by adiabatically lifting a mass of air from the cloud-base level. The observations of icing conditions reported herein were all made during winter and spring in situations in which the temperature at the base of the clouds was near freezing or lower and in which the vertical extent of the cloud development did not often exceed 6000 or 8000 feet. If those conditions are taken as representative for the icing season in northern United States, it would appear reasonable to accept a cloud-base temperature of 32° F and vertical extent of 8000 feet as representing the maximum cumulus icing condition likely to occur with appreciable frequency in northern United States during winter. Under these conditions, the calculated maximum liquid water concentration is 2.5 grams per cubic meter and the corresponding temperature is approximately 0° F. The corresponding value of mean-effective diameter was estimated from the data in figure 5. It was noted that the seven observations of more than 1.2 grams per cubic meter water content all had mean-effective drop diameters in the relatively narrow range from 17 to 23 microns. The average of these observations, 20 microns, was chosen as the probable value of mean-effective diameter corresponding to a maximum water content of 2.5 grams per cubic meter at a temperature of 0° F.

It should be recognized that the foregoing maximum icing condition was derived from an assumed cloud-base temperature of 32° F. If warmer weather conditions are considered, the maximum icing condition increases considerably. As an example, the conditions in the upper portion of a tall summer cumulus cloud will be calculated. Surface conditions are assumed as follows: pressure altitude, 400 feet, temperature, 90° F; dew point, 75° F; mixing ratio, 19.0 grams of water vapor per kilogram of dry air. If this surface air is lifted adiabatically, condensation occurs at 3600 feet pressure altitude and 71.5° F. Suppose the cloud extends to 23,000 feet pressure altitude just before precipitation begins. The condition at 22,000 feet would be as follows: temperature, 22.5° F; liquid water content, 7.6 grams per cubic meter. This represents an extremely severe icing condition; in fact, if the water content were reduced by 50 percent due to precipitation and mixing, it would still be an extremely severe condition. There is reason to believe that such conditions occur frequently in warm, moist climates where convective showers are common as along the Gulf Coast in summer. The severe icing conditions, however, are sharply limited both in space and time, and therefore would very rarely be encountered unless deliberately sought.

In connection with the problem of defining the maximum icing condition in which an ice-prevention system should be expected to provide protection, it is necessary to define the most severe icing condition likely to be met with a given airplane rather than the most severe icing condition which can ever occur. This presents a problem similar to that involved in the design of airplane structures to resist turbulence. For example, it is not considered necessary to design airplanes to withstand the conditions occurring in tornados, and yet such storms are by no means rare in the United States. The heaviest icing conditions, though much larger than tornados, are still quite limited both in extent and duration and are parts of cloud systems which ordinarily can easily be recognized and avoided by experienced pilots. Thus, while there is reason to believe that the concentration of supercooled water near the tops of cumulus clouds may occasionally reach 2.5 grams per cubic meter in winter in the Pacific Northwest and 6 or 7 grams per cubic meter in summer near the Gulf Coast, it is estimated that the highest value likely to be encountered in the course of all-weather transport operations in the United States is about 2.0 grams per cubic meter. The corresponding estimated values of mean effective drop diameter and temperature are 20 microns and 0° F. The most probable duration of flight (at 160 mph) in this condition, if it is encountered, is estimated to be about 1 minute, and the maximum duration a little less than 2 minutes, as will be shown below.

<u>The relation between intensity and maximum extent of icing conditions</u>.- Because of the facts that heavy icing conditions were observed only in cumulus clouds and that cumulus clouds are always rather limited in horizontal extent, a study of the data was made in an effort to define a relation between the extent and intensity of icing conditions. Unfortunately, data on the linear dimensions of the icing conditions were not obtained. The duration of flight in continuous icing was therefore used as a measure of the extent of the conditions although in several cases the airplane was flown back and forth in a single cloud formation, thus giving rise to larger duration than would have been required for a straight flight. Figure 13 shows the relation between the duration of periods of flight in continuous icing conditions and the average liquid water content during the periods. The plotted points are for individually observed cases and the line represents the estimated relation between average water content and maximum duration. It is fully relized that this estimate is uncertain due to the limited amount of data upon which it is based. It should be of some value, however, in indicating in at least a roughly quantitative way the inverse relationship which exists between a specified icing condition and the probable duration of flight in that condition. In the application of these results to the problem of evaluating the requirements for ice protection in all-weather transport operations, it should be remembered that on the research flights during which these data were collected, the flight path was chosen with the object of maximizing the severity and

duration of the icing conditions, while in ordinary operations the flight path would be chosen to reduce or eliminate the icing conditions. For this reason it is believed that the line in figure 13 represents a conservative estimate of the relation between the intensity and maximum duration of icing conditions as they would be encountered in normal all-weather transport operations in the United States.

It is noted that the line in figure 13 indicates a maximum duration of a little less than 2 minutes for a liquid water content of 2.0 grams per cubic meter. Since it is highly unlikely that the maximum duration will be encountered on the rare occasions when the highest water content occurs, the more probable value of 1 minute was chosen to correspond with the maximum icing condition defined above.

Maximum continuous icing conditions.- The results of the foregoing discussion of the extent of icing conditions as related to their intensity suggest a need to define the maximum icing condition likely to occur over a large enough area to make it necessary to provide for continuous operation in this condition. This condition will exist in layer-type clouds since cumulus clouds are by their nature discontinuous. The maximum liquid water content observed in layer clouds during this investigation was about 0.7 gram per cubic meter, which is the same as the maximum reported from the Army Air Forces Ice Research Base at Minneapolis, Minn. These facts and the data in figure 13 on the relation between liquid water content and duration of flight in icing conditions suggest that a reasonable estimate of the maximum water content likely to be encountered for periods of 20 minutes or longer at a true airspeed of 160 miles per hour would be approximately 0.8 gram per cubic meter. Since this condition is expected to occur in layer clouds (stratocumulus), a reasonable estimate of the concurrent values of temperature and mean-effective drop diameter was made from an examination of the data for layer clouds in figures 5 and 8. The values chosen were 20° F and 15 microns.

The possibility of more severe icing conditions with lower values of water content and larger drop sizes should not be overlooked. A reasonable extrapolation of the data in figure 5 suggests a condition of 0.5 gram per cubic meter at a mean-effective diameter of 25 microns as a definite possibility in layer clouds.

Since the temperature, as well as the liquid water content, is of primary importance in the design of thermal systems for ice protection, the relation between temperature and maximum water content for continuous icing conditions should be determined. It has been pointed out that in icing conditions of very limited extent, as found in cumulus clouds, very low temperatures may occur with high values of liquid water content. In the case of the more extensive icing conditions in layer clouds, however, a positive relationship appears to exist between temperature and maximum liquid water content. Proposals to define this relationship have been given in references 6 and 14, and are reproduced in figure 8.

The curve from reference 6 depicts conditions 3000 feet above the base of a cloud formed by adiabatic processes. Subsequent experience has shown that the values of water content indicated by this curve are much higher than ordinarily observed in layer clouds. Apparently stratus and stratocumulus layers 2000 to 3000 feet thick are not generally characterized by a constant total mixing ratio. The data from reference 14 are based upon observations made on the summit of Mt. Washington where orographic factors have a very marked effect on the liquid water content.

The lowest curve in figure 8 indicates the relation between maximum liquid water content and temperature in layer clouds as observed in this investigation. Since this curve is based upon only a small number of observations and since it has no theoretical basis, it should be used with caution. Because of the small amount of data available for layer clouds at very low temperatures, it is not possible at this time to define the maximum probable low-temperature continuous-icing condition.

Typical icing conditions.- The conditions defined above as the most severe likely to be encountered in all-weather transport operations will only rarely be observed. Conditions ordinarily met with are much milder. It is estimated that values of liquid water content as high as 0.3 gram per cubic meter in layer clouds and 0.8 gram per cubic meter in cumulus clouds will be encountered with sufficient regularity to be regarded as normal or typical icing conditions. The corresponding mean-effective diameter is likely to be anywhere in the range from 8 to 20 microns.

Icing conditions with very large drops.- Another important aspect of the problem of the definition of maximum icing conditions concerns the largest drop diameters likely to be encountered and the probable corresponding values of water content. Examination of the data in figure 5 indicates that in about 1 observation in 50 the mean-effective diameter is over 35 microns. This limited amount of data for clouds with large mean-effective drop diameter indicates that the water content is likely to be low, 0.25 gram per cubic meter or less. It should be pointed out, however, that the data in figure 5 are in terms of mean-effective diameter and that with certain types of size distribution, appreciable amounts of water may be present in the form of drops 35 microns or more in diameter even though the mean-effective diameter is as low as 20 microns. It would therefore appear that small amounts, for example about 0.1 gram per cubic meter, of drops of 35 to 50 microns diameter should not be regarded as exceptional. Because of the high collection efficiency and wide areas of impingement associated with the larger drops, the presence of even small amounts of water in drops of 35 microns or larger diameter has an important effect upon the requirements for thermal ice prevention. More detailed data on drop-size distribution are very desirable for this reason.

Freezing rain.- Since freezing rain has not been observed in the course of this investigation, no observational data can be presented. The subject should be mentioned, however, if only to emphasize the fact that the general discussion of icing conditions presented herein does not necessarily apply to freezing rain.

The meteorological conditions ordinarily required for the formation of freezing rain are an inversion, usually frontal, with temperatures above freezing in the warm air above and below freezing in the cold air below the inversion. The temperature range of the occurrence of freezing rain is rather small, since the raindrops freeze and become sleet at temperatures only a few degrees below freezing. The rate of precipitation in freezing rain is usually less than 0.1 inch per hour which corresponds to a liquid water content of about 0.2 gram per cubic meter. The drops are usually between 500 and 1000 microns in diameter which is large enough to give substantially 100-percent collection efficiency on all aircraft components. It should be noted in passing that any cloud with drops larger than 35 or 40 microns in diameter is likely to be erroneously reported by pilots as "freezing rain" because such large cloud droplets, on striking the windshield, present an appearance similar to raindrops.

CONCLUSIONS

The following rules for estimating the intensity of icing conditions are based upon a study of flight measurements of icing conditions, supplemented by an analysis of the physical processes which are important in determining the distribution of liquid water in clouds. They are expressed in terms of the scale of icing intensity used by the Weather Bureau in reporting icing conditions at mountain stations.

1. In layer clouds with precipitation, icing intensities greater than a trace are unlikely except near the edges of the precipitation area or where the precipitation is very light or has just begun.

2. In clouds composed entirely of liquid drops the icing intensity usually varies with temperature and height above the cloud base as indicated by the theory for adiabatic lifting, but the actual water content is ordinarily less than the calculated value.

3. In layer clouds without precipitation, icing conditions are usually light but are occasionally moderate near the tops of thick layers.

4. Moderate and heavy icing conditions usually occur only in cumulus clouds, but conditions in the upper portions of unusually thick stratus or stratocumulus layers occasionally reach moderate intensity.

5. Icing conditions in cumulus clouds are highly variable and in the upper portions of tall clouds may be very severe.

6. During winter, heavy icing conditions are not likely to be encountered continuously for more than 2 to 3 minutes.

Analysis of the available observational data supplemented by considerations of the physical processes involved in the formation of icing conditions has led to the following tentative estimates of the most severe icing conditions likely to be encountered in the course of all-weather transport operations in the United States:

Cloud type	Duration (at 160 mph)	Liquid water content	Average drop diameter	Temperature
cumulus	1 minute	2.0 gm/m^3	20 microns	0° F
stratus or stratocumulus	20 minutes or longer	0.8 gm/m^3	15 microns	20° F
stratus or stratocumulus	20 minutes or longer	0.5 gm/m^3	25 microns	20° F

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APPENDIX

Temperature Correction for Kinetic Heating

The true temperature of the undisturbed air was obtained by subtracting the following correction from the observed temperature when flying in clear air:

$$\Delta T = 1.77\, \alpha \left(\frac{U_T}{100}\right)^2$$

where ΔT is the correction in degrees Fahrenheit, and U_T is the true airspeed in miles per hour. The value of the constant α must be determined experimentally for any particular installation. For full adiabatic compression at a stagnation point $\alpha = 1.0$; for the particular installation described herein $\alpha = 0.93 \pm 0.05$. This value was determined by making successive runs at various speeds at a constant altitude over the same area in approximately homogeneous air.

When the air contains liquid water drops there is apparently no accepted theory for calculating the temperature rise. Hardy assumed in reference 5 that the ratio of the temperature rise in wet air to that in dry air is equal to the ratio of the specific heats of dry and wet air at constant pressure. The use of the ratio of the saturated and dry adiabatic lapse rates is recommended by the Army Air Forces for use in correcting wet bulb readings in clear air and both wet and dry bulb readings in "wet cloud." This differs only slightly from the ratio used by Hardy, the difference being due to a difference between the adiabatic and isobaric rates of change of saturation mixing ratio with temperature.

In order to determine experimentally the ratio of the kinetic temperature rise in clouds to that in clear air, test runs were made at various speeds in uniform stratus clouds at temperatures of 15° to 25° F and 50° to 60° F. The tests at 15° to 25° F were conducted in Minnesota during the winter of 1944–45 with the C-46 airplane. The thermometer used was of the mercury-in-glass type mounted with the bulb pointing downwind and shielded as shown in figure 14. The tests at 50° to 60° F were conducted in stratus clouds off shore near San Francisco with a U.S. Navy blimp and a P-38 airplane. A resistance thermometer suspended on a cable below the blimp was used to make a sounding through the cloud layer just before and just after the high-speed runs with the P-38. The thermometer on the P-38 was a resistance thermometer with the sensitive element exposed in a mounting designed to obtain the stagnation temperature. The results of these tests are presented in figure 15 which also includes curves showing the ratio of the specific heats of dry and wet air at constant pressure and the ratio of the wet and dry adiabatic lapse rates.

Since the adiabatic lapse-rate ratio shows the best agreement with the observations, it has been used in this investigation to determine the kinetic heating correction for all observations of temperature within clouds. It was observed that very small amounts of liquid water are sufficient to reduce the kinetic temperature rise to approximately the moist adiabatic value, hence no attempt has been made to use intermediate values of the correction for low values of liquid water content. Since no measurements of the kinetic temperature rise have been made in clouds composed of ice crystals, the corrections were made in the same way as in clouds composed of liquid drops. The error involved in this procedure is unknown but may reasonably be assumed to be less than the difference between the dry and wet corrections, which difference, at the temperature and speeds prevailing in this investigation, was usually between 1° and 2° F.

The validity of the correction just described for kinetic heating in clouds does not depend upon any assumptions regarding the processes of evaporation which may occur at or near the thermometer. The use of the ratio of the adiabatic lapse rates is justified on purely empirical grounds, since the observed ratio of wet to dry values of kinetic temperature rise agrees fairly well with the lapse-rate ratio over a wide range of temperature.

Measurements by the Rotating-Cylinder Method

In the present investigation, the rotating cylinder method was used essentially as described in reference 8, except that the exposure time was generally about 1 minute instead of 5 minutes, and the average diameter of the ice formation was determined by calculation instead of by actual measurement. The calculation was based upon an assumed ice density of 0.8 gram per cubic centimeter. With the small amounts of ice collected during 1-minute runs, this method was calculated to give less error than direct measurements of diameter made in flight.

Data on drop-size distribution in icing clouds are usually presented in terms of a "volume" rather than a "number" distribution, since the amount of water in drops of a given size is of greater importance than the number of drops. One form of volume-distribution curve is constructed by plotting, as a function of diameter, the percent of the total liquid water content of the cloud which is contained in drops smaller than that diameter. A distribution curve of this type is presented in figure 16. This curve was drawn from data appearing in reference 8 which were obtained by the sooted slide technique described therein. On a distribution curve of this type, the volume median diameter is the value of diameter determined by the point at which the curve crosses the 50-percent line. The volume median diameter is thus defined by the property that there is as much water in the drops larger than the volume median diameter as there is in drops smaller than the volume median diameter. In the example shown in figure 16, the volume median diameter is 11.9 microns.

The data presented in reference 11, showing the collection efficiency of cylinders as a function of K, a parameter involving drop diameter, are given for five assumed distributions of drop size, A, B, C, D, and E. Distributions A, B, and E are shown in figure 16 for a volume median diameter of 12 microns. Distributions C and D which are intermediate between B and E are omitted for simplicity. The values of drop diameter obtained from rotating-cylinder observations by the method described in reference 11 are called mean-effective diameter. The mean-effective diameter is equal to the volume median diameter if the actual distribution is similar to the assumed distribution. It is not known how closely the assumed drop-size distributions resemble the actual distributions found in clouds. Since the limited amount of data available from the four-cylinder apparatus indicated the presence of distributions covering the entire range from A to E, the curves based on distribution C were arbitrarily chosen to be used in reducing the data taken with the two-cylinder apparatus.

The errors involved in calculating the liquid water content and mean-effective diameter from the two-cylinder data have been estimated by considering the errors inherent in measuring the quantities used in the calculations. The results, which are shown in the following table, are based on a liquid water content of 0.5 gram per cubic meter and an average drop diameter of 10 microns.

Source of error	Estimated amount of error	Resulting percent error (E)	
		Water content (percent)	Drop diameter (percent)
Weighing sample 1/8-in. cylinder	0.02 gram	2.6	2
Weighing sample 1-in. cylinder	.03 gram	1.0	1
Assumed density of ice	.08 $\frac{gm}{cm^3}$	2.5	2
Timing exposure	1.5 sec	2.4	0
True airspeed	$2\frac{1}{2}$ mph	1.5	0
Miscellaneous other errors	----	1.0	1
Error due to using "C" distribution curves for unknown distribution	----	up to 3	up to 3

Total error	Water content (percent)	Drop diameter (percent)
Maximum total error (ΣE)	14	9
Estimated resultant error $\left(\sqrt{\Sigma E^2}\right)$	5.7	4.4

Ames Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Moffett Field, Calif., June 23, 1947.

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TABLE I. SUMMARY OF METEOROLOGICAL DATA OBSERVED IN ICING CONDITIONS

Icing Condition Number	Flight Number	Date	Time (Pacific Standard)		[1]Liquid Water Content (g/m³)		[2]Mean Effective Drop Diam (microns)			[3]Drop Size Distribution	No. of rotating cyl. obs.	Max. Diam. by Area of Catch Method (microns)		Temperature (°F)		Pressure Altitude (feet)	
			beginning	ending	average	maximum	mean	max.	min.			greatest	least	max.	min.	min.	max.
1	20	2-28-46	1:45 PM	2:25 PM	Trace	.25						17	13	10	4	12,000	13,000
2	22	3- 2-46	10:40 AM	11:20 AM	Trace	Trace						--	--	32	8	4,500	11,300
3	23	3- 2-46	2:50 PM	4:07 PM	.52	1.4						44	11	12	-7	9,200	13,500
4	24	3- 3-46	1:00 PM	2:20 PM	--	.7						29	15	24	-2	5,300	12,700
5	25	3-19-46	3:41 PM	3:51 PM	--	.7		14			1	--	--	24	20	7,000	7,800
6	26	3-21-46	4:00 PM	5:00 PM	.38	.7	14	18	11		8	17	12	19	14	10,200	11,100
7	27	3-22-46	2:30 PM	2:45 PM	.36	.7	17	18	17		3	--	--	11	8	8,400	8,900
8	27	3-22-46	3:15 PM	3:35 PM	.06	.2	--	--	--		4	24	14	19	15	6,500	7,300
9	28	3-24-46	11:15 AM	12:00 M	.48	.8	14	15	12		6	15	12	18	13	6,600	7,800
10	28	3-24-46	12:55 PM	1:25 PM	.2	.3	--	19	14		3	20	12	3	2	10,700	11,100
11	28	3-24-46	3:30 PM	3:45 PM	.4	.5	--	28	14		3	--	--	-4	-8	12,800	13,600
12	29	3-25-46	1:55 PM	2:45 PM	0	0	0	0	0		0	0	0	23	19	9,000	11,000
13	30	3-27-46	4:00 PM	5:00 PM	Trace	.05	--	8	--		1	--	--	26	15	8,000	12,200
14	31	3-29-46	10:30 AM	11:30 AM	.61	.9	14	18	8		7	20	15	16	9	7,100	9,000
15	31	3-29-46	3:50 PM	6:00 PM	.18	.5	11	18	3		4	18	15	14	-2	9,100	13,200
16	32	3-30-46	11:03 AM	11:05 AM	--	.6	--	26	--		1	--	--	15	--	12,500	-----
17	32	3-30-46	1:17 PM	1:19 PM	--	.3	--	45	--		1	--	--	7	--	11,100	-----
18	32	3-30-46	1:40 PM	2:30 PM	.64	.9	13	17	10		6	--	--	20	13	7,800	9,800
19	33	3-31-46	11:00 AM	1:45 PM	.44	1.0	11	17	7		12	54	18	28	7	5,700	11,600
20	34	4- 1-46	3:10 PM	4:40 PM	.53	.8	13	14	--		6	19	17	27	11	6,300	10,200
21	35	4- 3-46	4:22 PM	4:47 PM	.13	.3	13	18	5		4	--	--	16	9	9,100	12,100
22	36	4- 5-46	5:25 PM	5:57 PM	.48	.7	12	14	10		5	--	--	27	24	4,500	5,000
23	37	4- 6-46	12:43 PM	1:30 PM	.22	.4	13	14	12		5	--	--	25	20	4,600	5,800
24	38	4- 7-46	12:00 M	4:50 PM	.61	1.1	17	26	12		10	--	--	18	3	11,800	15,100
25	38	4- 7-46	12:00 M	4:50 PM	.11	.2	12	29	3		11	--	--	18	3	11,800	15,100
26	39	4- 8-46	12:56 PM	3:40 PM	.34	.5	10	13	5		18	--	--	27	23	8,500	11,500
27	40	4- 9-46	9:45 AM	10:55 AM	.08	.2	19	27	14		8	--	--	26	22	8,600	9,700
28	40	4- 9-46	3:30 PM	4:25 PM	.38	1.1	17	22	14		9	--	--	4	-19	14,800	20,300
29	42	4-13-46	2:50 PM	3:40 PM	.16	.3	6	7	3		6	--	--	24	16	11,600	13,800
30	43	4-14-46	10:40 AM	12:22 PM	.15	.3	8	10	7		4	--	--	29	24	10,500	10,900
31	43	4-14-46	12:22 PM	2:30 PM	.40	.6	10	14	3		25	--	--	26	23	10,200	11,000
32	44	4-15-46	10:00 AM	10:90 AM	.05	.1	--	20	--		2	--	--	23	22	9,900	11,700
33	44	4-15-46	11:20 AM	12:15 PM	Trace	.05	--	--	--		1	--	--	24	16	11,600	13,800
34	46	4-25-46	4:00 PM	5:23 PM	.11	.3	30	50	18	----	12	--	--	28	17	8,900	10,600
35	47	4-26-46	12:30 PM	2:30 PM	.38	.6	13	19	11	E in Cu	8	--	--	29	23	5,000	6,600
			4:15 PM	5:15 PM						A in Sc							
36	48	4-28-46	10:50 AM	2:00 PM	.05	.2	10	12	7	C	8	--	--	30	19	8,300	12,500
37	48	4-28-46	4:20 PM	6:00 PM	.15	.4	13	21	8	--	13	--	--	25	15	10,200	12,900
38	49	4-29-46	11:05 AM	11:45 AM	.35	.7	24	44	14	--	5	--	--	15	7	7,600	9,400
39	49	4-29-46	11:53 AM	12:20 PM	.95	1.9	19	22	15	E and C	7	--	--	5	-5	10,200	13,000
40	49	4-29-46	12:45 PM	1:15 PM	.18	.3	23	28	16	A and E	6	--	--	15	11	7,800	8,600
41	49	4-29-46	1:15 PM	1:45 PM	1.01	1.5	17	18	15	E and D	5	--	--	14	8	7,900	9,400
42	49	4-29-46	3:55 PM	6:00 PM	.57	1.5	20	30	9	E	19	--	--	20	7	6,400	9,500

[1]Values of liquid water content in conditions 1 to 4 are calculated from the thickness of ice formed in one minute on a stationary rod. Values given for conditions 5 through 42 are from rotating-cylinder measurements.

[2]Values of drop size are from rotating-cylinder measurements.

[3]Size distribution as defined in reference 15 given only for cases in which four-cylinder data were available.

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TABLE I. CONCLUDED

Icing Condi-tion Number	[4]Relative extent of Cloud Masses	[5]CLOUD TYPE	Cloud Composition	[6]Air Mass Classifi-cation	Synoptic Situation	LOCATION	REMARKS
1	Scattered	Cumulus and Cumulonimbus	mostly snow			Southeastern Wyo.	
2	Continuous	Altostratus & Nimbostratus	snow	MP	Pre frontal	Eastern Oregon	
3	Scattered	Cumulus and Cumulonimbus	mostly water	MP	Post Cold Front	Eastern Oregon	
4	Scattered	Cumulus and Stratocumulus	water & snow	MP	High and Rising	No. California	Same area as icing condition 2. .7gm/m³ measured over Siskiyou mountains at 12,700 ft.
5	Scattered	Cumulus	water	MPK	Trough	Cent. Calif. Coast	
6	Broken	Altocumulus	mostly water			Western Nevada	Total accumulation, 2 inches, some snow showers.
7	Broken	Cumulus	water	MPK	Post Cold Front	Oregon	
8	Broken	Cumulonimbus & Stratocumulus	mostly snow	MPK	Post Cold Front	Oregon	
9	Broken	Cumulus and Cumulonimbus	mostly water	MP	Post Cold Front	Central Oregon	1 inch in 15 minutes.
10	Broken	Cumulus and Cumulonimbus	water & snow	MP	Post Cold Front	Idaho	Bases at 9000 feet.
11	Scattered	Cumulonimbus	water & snow	MP	Post Cold Front	Idaho	
12	Continuous	Altostratus	snow	MP	New Mexico Low	Southeastern Wyo.	
13	Continuous	Altostratus & Altocumulus	mostly snow	MP	Above Cold Front	Eastern Oregon	
14	Scattered	Cumulus	mostly water	MP	Post Cold Front	Central Oregon	
15	Scattered	Cumulonimbus & Altostratus	mostly snow	MP	Post Cold Front	Idaho	
16	One cloud	Cumulonimbus	mostly water	MP	On Cold Front	Utah	
17	-----	Cumulonimbus	mostly snow	MP	Post Cold Front	Eastern Calif.	Over Donner summit.
18	Broken	Cumulus and Cumulonimbus	mostly water	MP	Post Cold Front	Central Calif.	
19	Scattered	Cumulus and Cumulonimbus	water & snow	MP	Post Cold Front	Cent. Calif. Coast	
20	Scattered	Cumulus and Cumulonimbus	water & snow	MP	Nevada Low	Cent. Calif. Coast	Bases 4100 to 4400, 34° to 35°F
21	Continuous	Altocumulus	water & snow	MP	Pre frontal	Northern Calif.	Over Siskiyou mountains
22	Continuous	Stratus and Stratocumulus	water	MP	NW Gradient	Western Ore.	
23	Broken	Stratocumulus	water	MP	NW Gradient	Western Ore.	
24	Scattered	Cumulus and Altocumulus	mostly water	MP }	{ Flat pressure field	No. Nevada, Utah, & So. Wyo. }	Data for water clouds and snow clouds entered separately for same flight period.
25	Scattered	Cumulonimbus & Altostratus	mostly snow	MP }			
26	Continuous	Stratus and Stratocumulus	water	CP	Colorado Low	Southeastern Wyo.	Upslope stratus
27	Continuous	Stratus with Altostratus above	water & snow	CP	Pre-frontal	Western Nebraska	Stratus being depleted by snowfall from altostratus.
28	Scattered	Cumulonimbus	water & snow	CPK	Post Cold Front	Southeastern Colo.	Single convective cloud.
29	Scattered	Cumulus humulis	mostly water	MP	Post Cold Front	Northern Utah	
30	Broken	Stratocumulus	water	CP	Colorado Low	No. Utah & So. Wyo.	
31	Continuous	Stratus	water	CP	Colorado Low	Southeastern Wyo.	
32	Scattered	Altocumulus and Altostratus	water & snow	CP		Eastern Colorado	Patches of altocumulus in tenuous altostratus.
33	Scattered	Cumulus humulis	water	CP		Southern Wyoming	
34	Continuous	Altostratus	mostly water	MP	Frontal(cold f)	Oregon Coast	Large average drop diameter may be mixture of drizzle and cloud drops.
35	Broken	Cumulus and Stratocumulus	mostly water	MPK	Anticyclonic	Western Oregon	
36	Continuous	Altostratus	mostly snow	MP	Pre-frontal	Western Oregon	Total accumulation about 3/8 inches.
37	Broken	Altostratus and Altocumulus	snow & water	MP	Pre-frontal	Western Oregon	Total accumulation about 1-1/4 inches.
38	Scattered	Cumulus and Cumulonimbus	water & snow	MPK	Post Cold Front	Western Oregon	
39	Scattered	Cumulus bec. Cumulonimbus	water & snow	MPK	Post Cold Front	Western Oregon	
40	Continuous	Stratocumulus	water & snow	MPK	Post Cold Front	Western Oregon	
41	Scattered	Cumulus and Cumulonimbus	water & snow	MPK	Post Cold Front	Western Oregon	
42	Scattered	Cumulus and Cumulonimbus	water & snow	MPK	Post Cold Front	Western Oregon	

[4]"Scattered" indicates more clear air than cloud. "Broken" indicates more cloud than clear air. "Continuous" indicates unbroken cloud or only occasional small breaks.
[5]According to the classification presented in the International Atlas, Paris, 1932.
[6]M Marine; C Continental; P Polar; K indicates instability near the surface.

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TABLE II

OBSERVATIONS IN THE UPPER PORTION OF A LARGE CUMULUS CLOUD DURING THE PERIOD IMMEDIATELY FOLLOWING THE ONSET OF PRECIPITATION
(Icing Condition 39, table I)

Time (P.S.T.)	Temperature ($^{\circ}F$)	Pressure altitude (ft)	Liquid water content (gm/m^3)	Mean effective drop diameter (microns)
11:53$\frac{1}{2}$	5	10,400	1.9	17
11:54$\frac{1}{2}$	4	10,800	1.4	19
11:58	3	11,000	1.0	20
12:04	1	11,600	.8	22
12:05	0	11,600	.6	21
12:12	-2	12,500	.2	18

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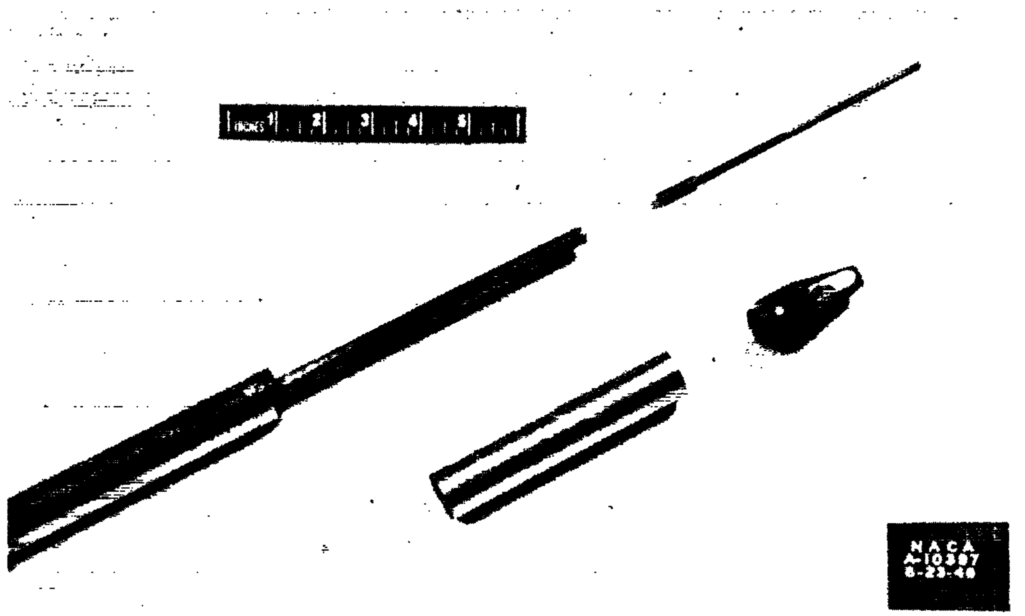
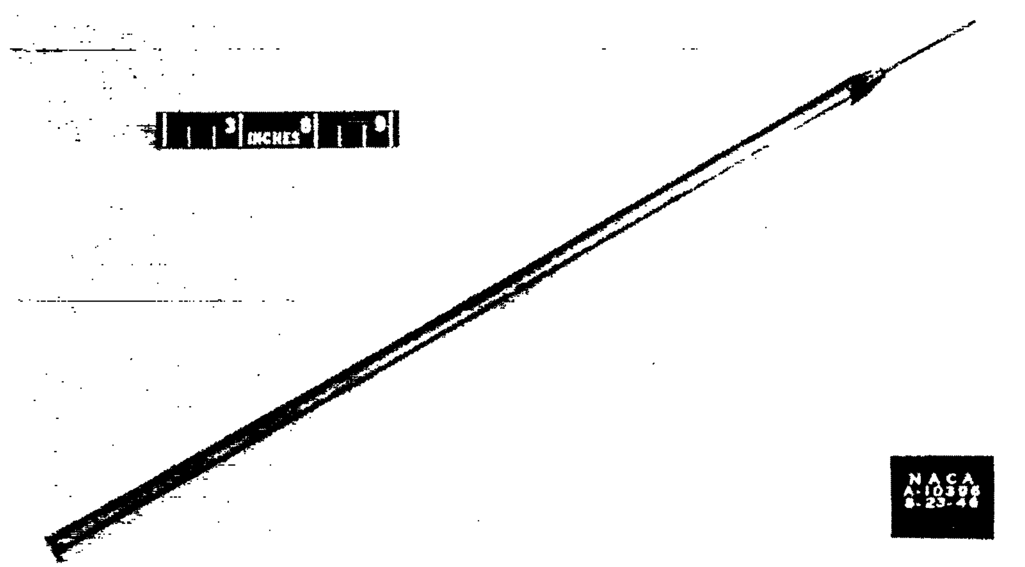
Figure 1.- Shielded free-air temperature thermocouple installation on C-46 airplane.



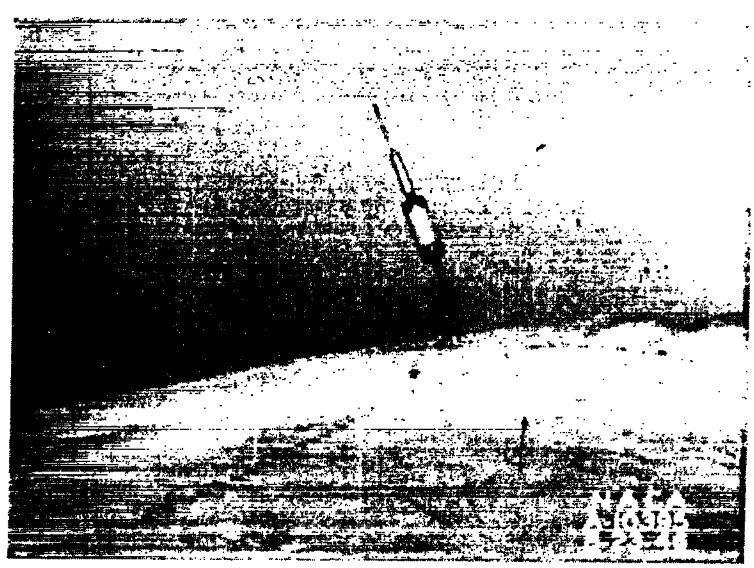
(a) Disassembled.



(b) Assembled.

Figure 2.- Manually operated rotating cylinders, two-cylinder assembly.

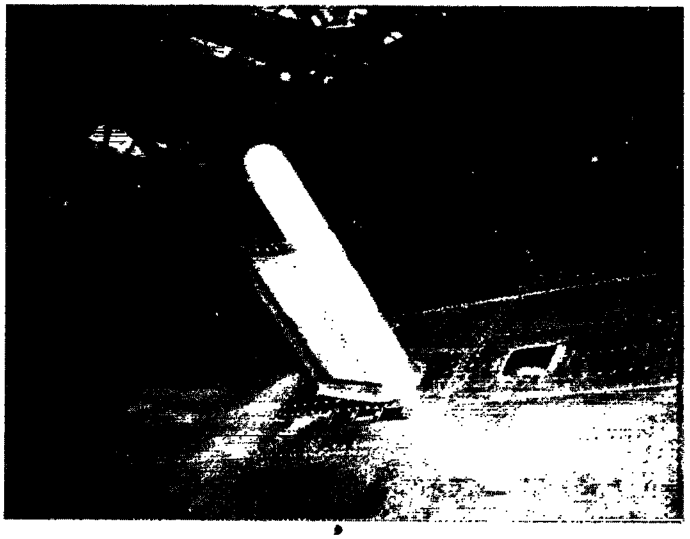
(a) In position for loading.



(b) In extended position.

Figure 3.- Four-cylinder motor-driven rotating cylinder apparatus.

(a) Cylinder ready for exposure.



(b) Cylinder in extended position.

Figure 4.- Cylinder for measuring area of drop impingement.

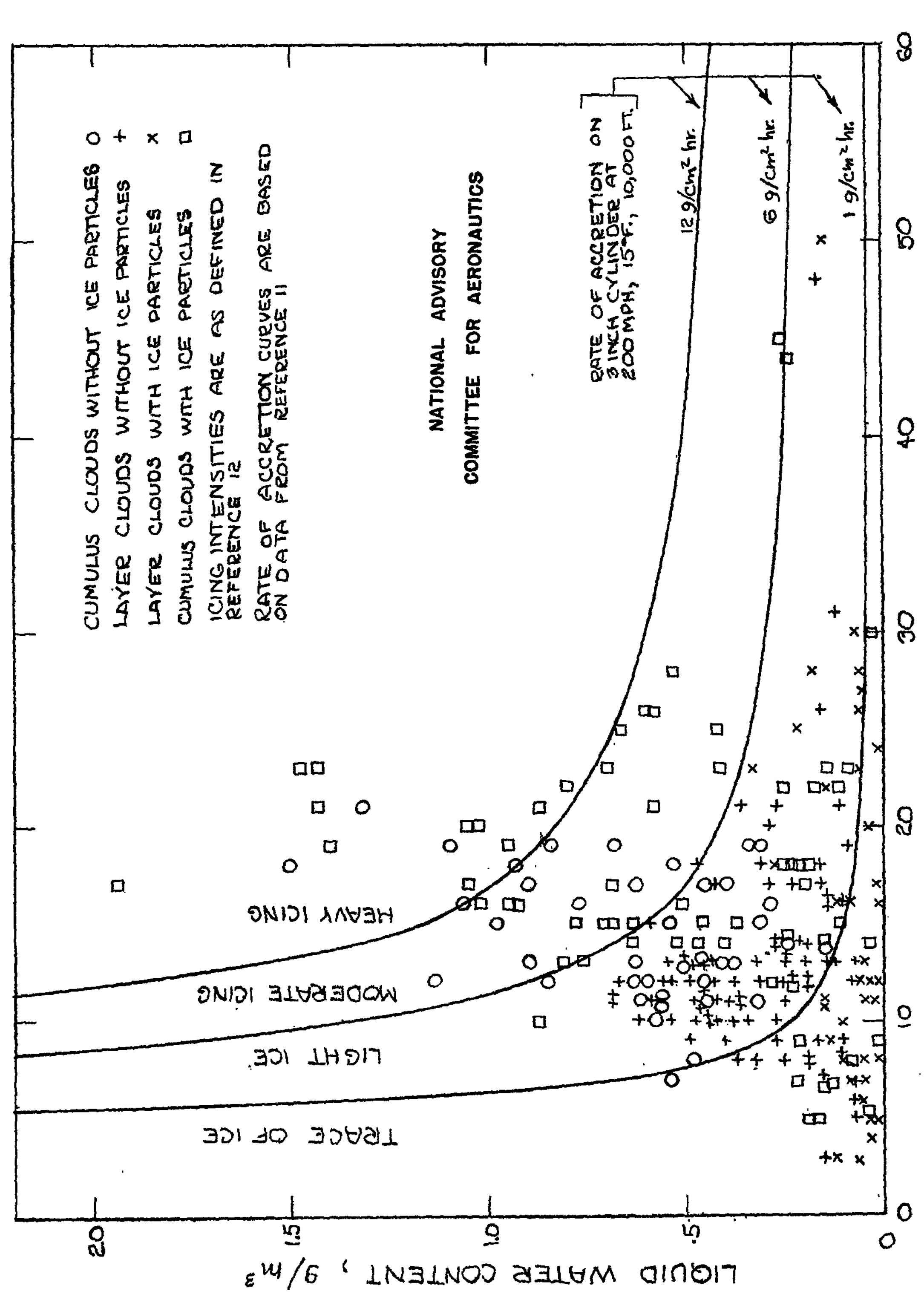


FIGURE 5.- LIQUID WATER CONTENT AND DROP SIZE BY ROTATING CYLINDER MEASUREMENT AS COMPARED WITH WEATHER BUREAU SCALE OF ICING INTENSITY

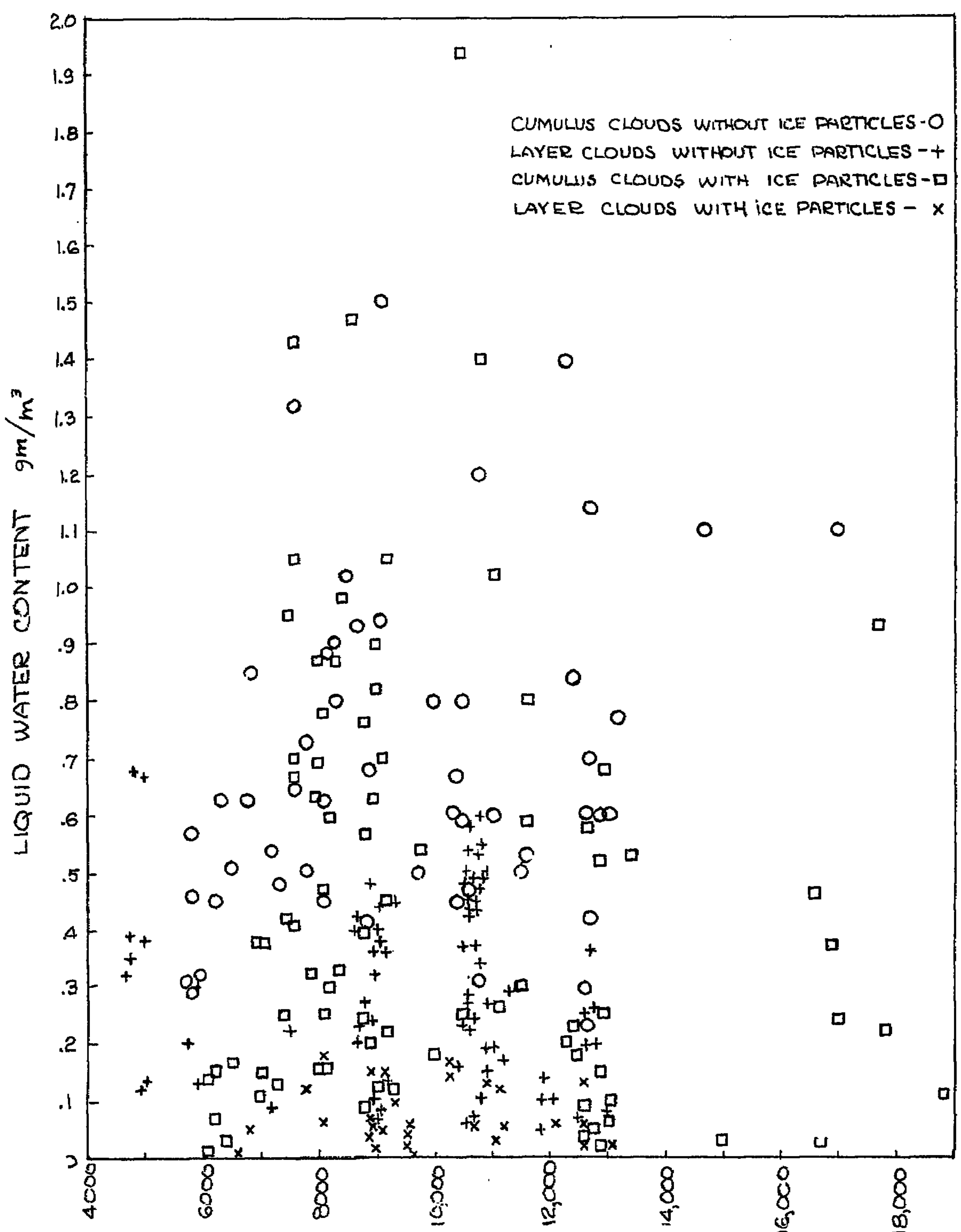


FIGURE 6.- LIQUID WATER CONTENT BY ROTATING CYLINDER MEASUREMENT AS RELATED TO PRESSURE ALTITUDE

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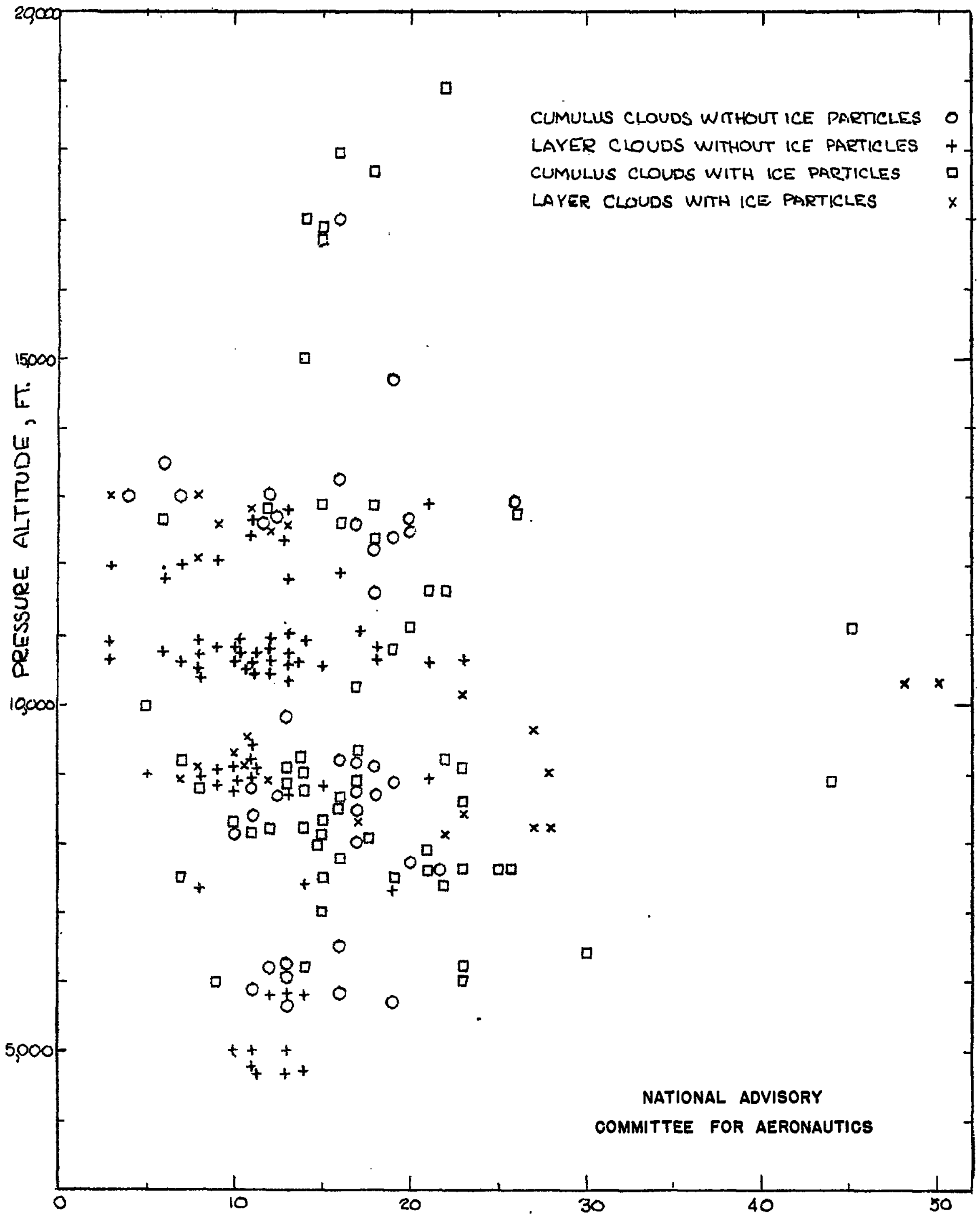

FIGURE 7.- DROP SIZE BY ROTATING CYLINDER MEASUREMENT AS RELATED TO ALTITUDE

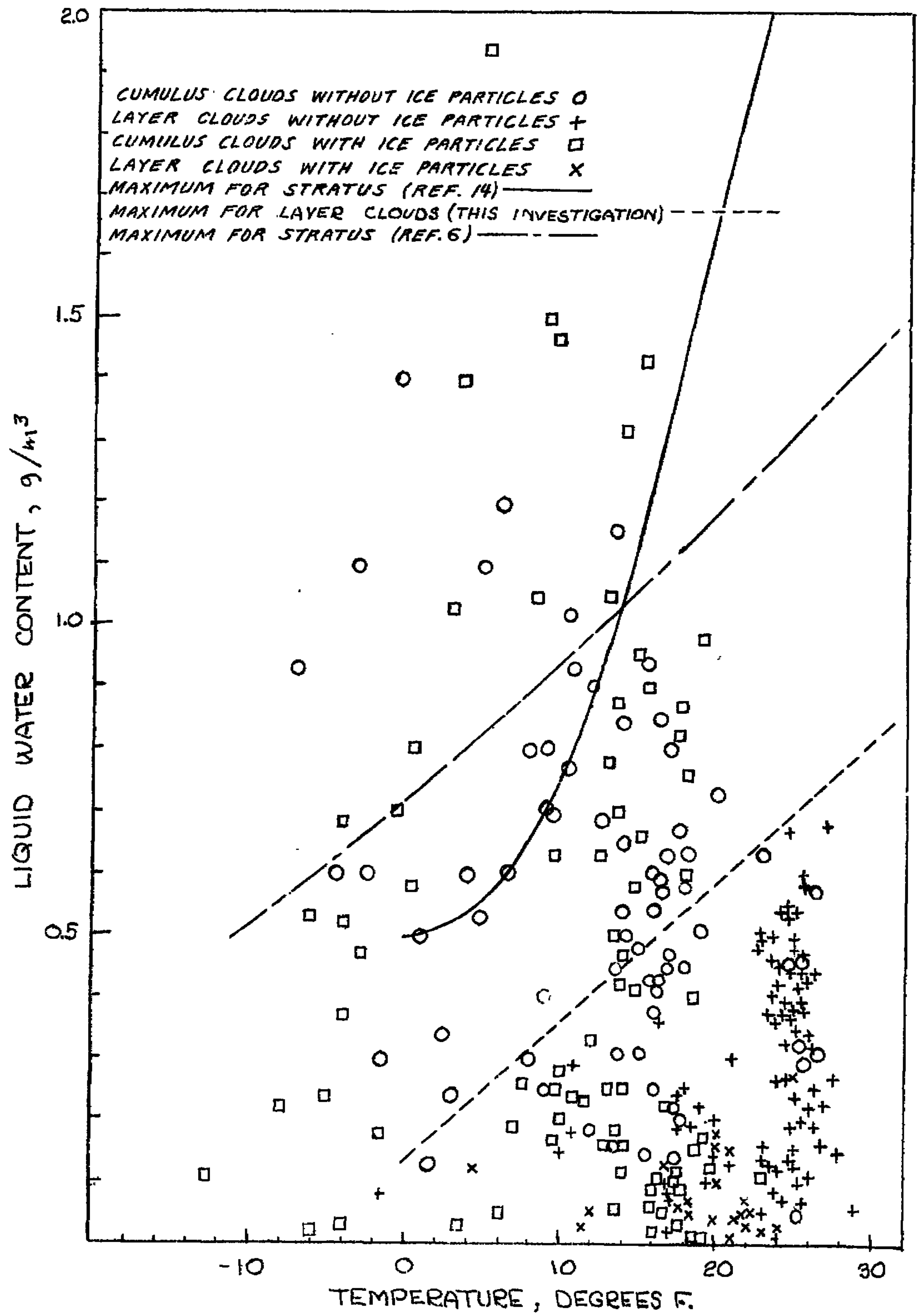

FIGURE 8.- LIQUID WATER CONTENT AS A FUNCTION OF FREE AIR TEMPERATURE. ROTATING CYLINDER MEASUREMENTS

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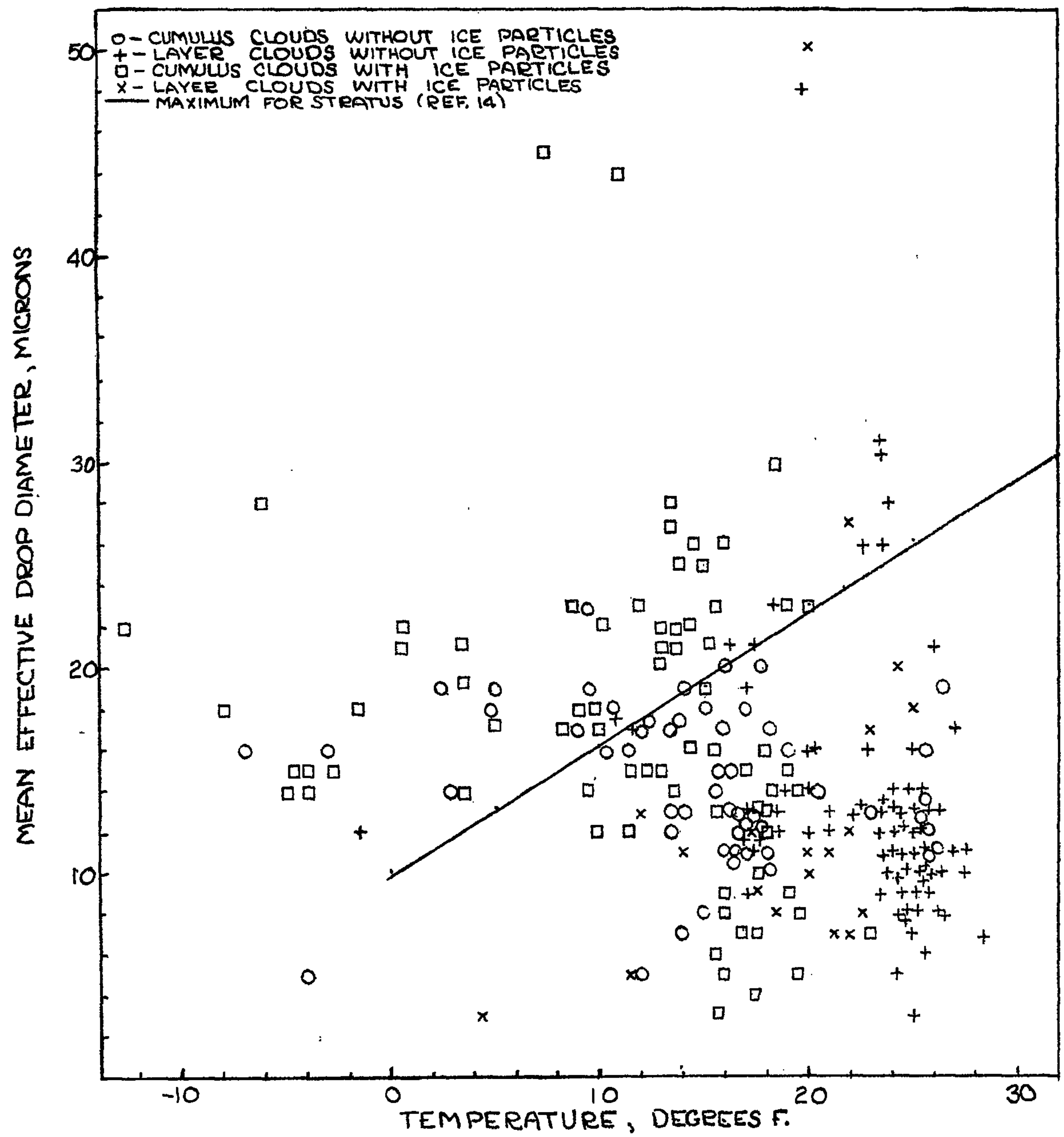

FIGURE 9.- DROP SIZE BY ROTATING CYLINDER MEASUREMENT AS RELATED TO FREE AIR TEMPERATURE.

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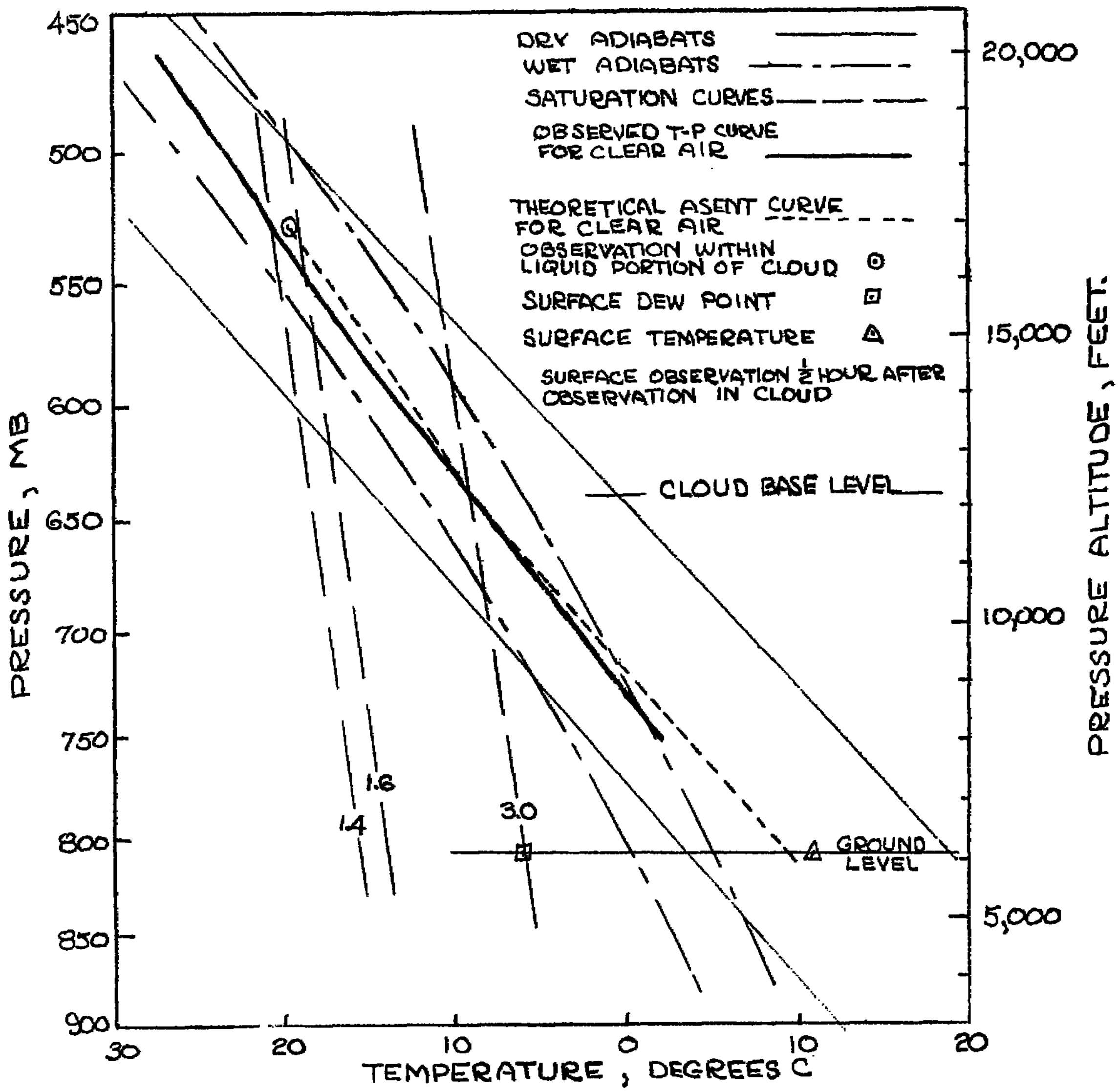

FIGURE 10.- DATA FROM THE INVESTIGATION OF A CUMULUS CLOUD NEAR CHEYENNE, WYOMING ON APRIL 9, 1946.

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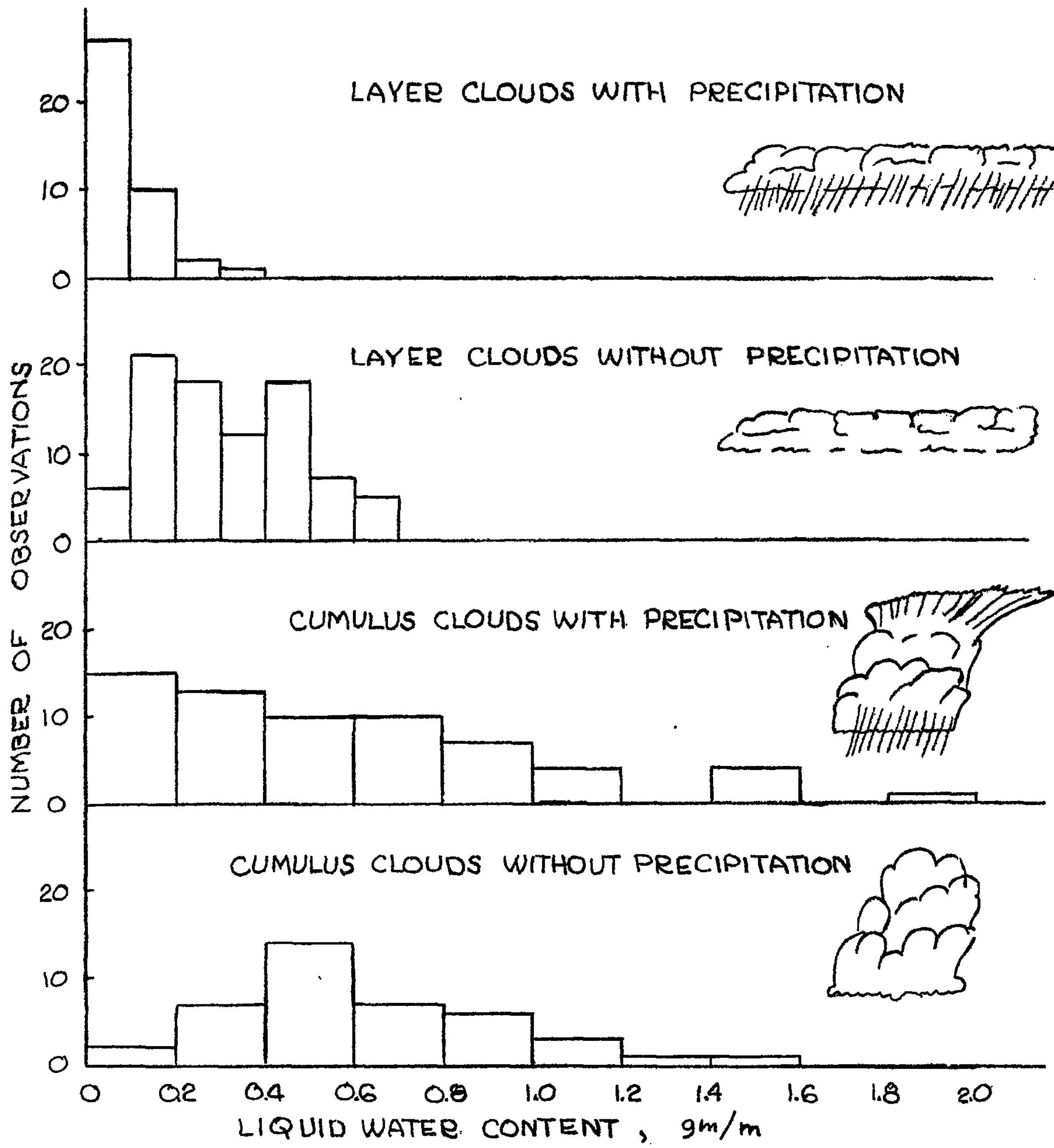

FIGURE 11.- FREQUENCY DIAGRAM ILLUSTRATING THE RELATION OF LIQUID WATER CONTENT TO CLOUD FORM AND COMPOSITION.

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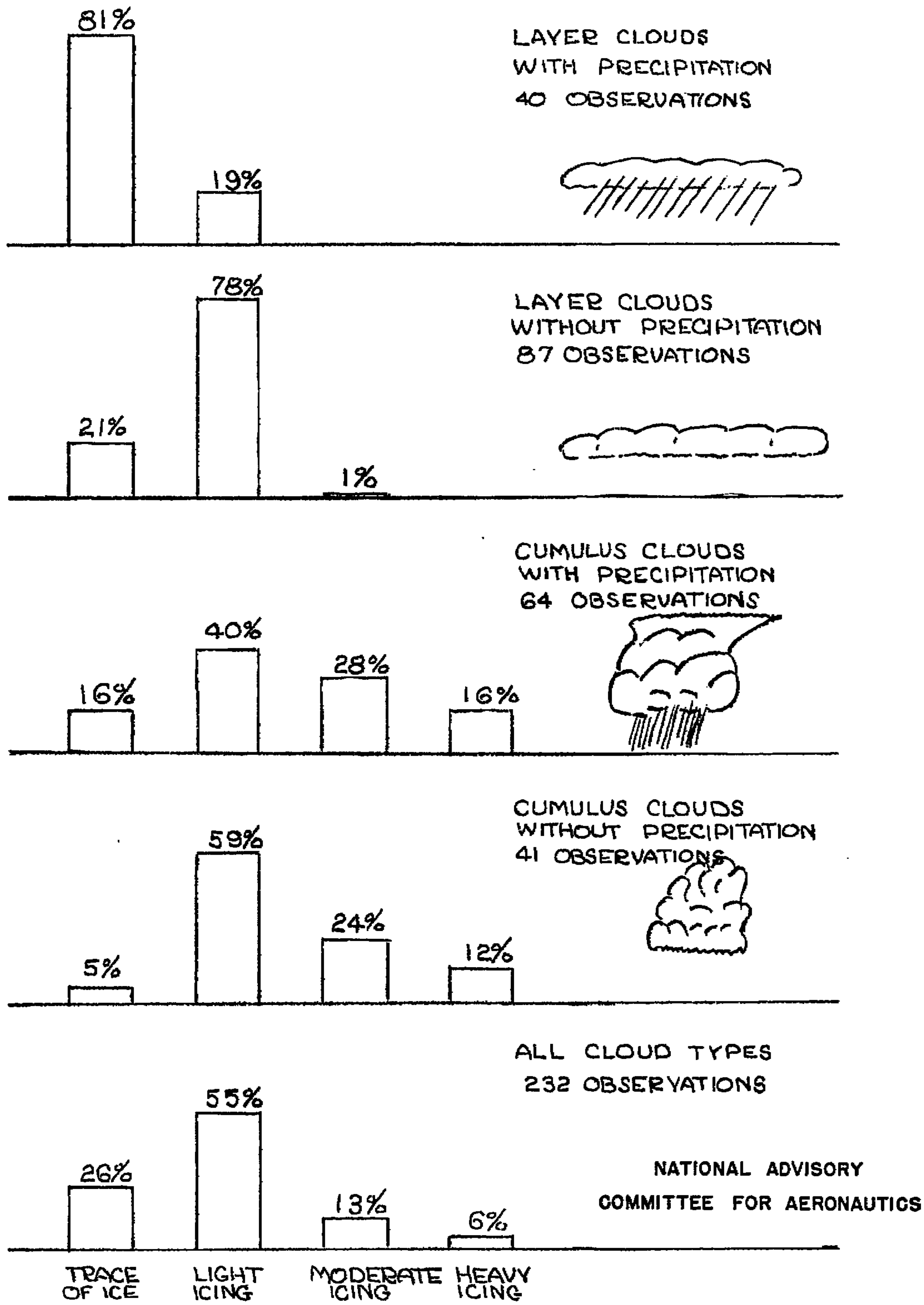

FIGURE 12.- RELATIVE FREQUENCY OF VARIOUS DEGREES OF ICING INTENSITY AS RELATED TO CLOUD FORM AND PRECIPITATION

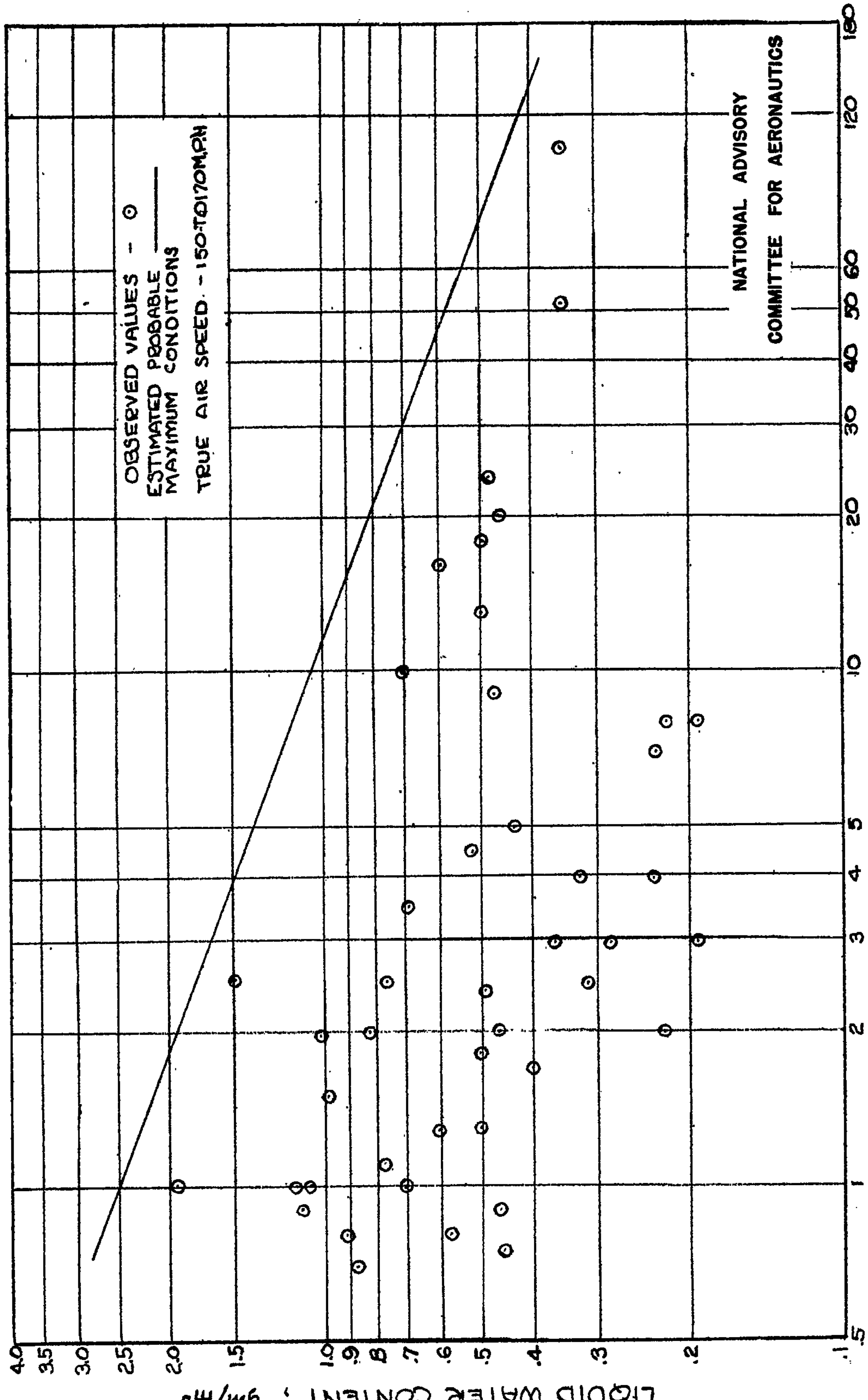

FIGURE 13.- AVERAGE LIQUID WATER CONCENTRATION IN WINTER ICING CONDITIONS AS A FUNCTION OF MAXIMUM DURATION OF FLIGHT IN THE CONDITION.

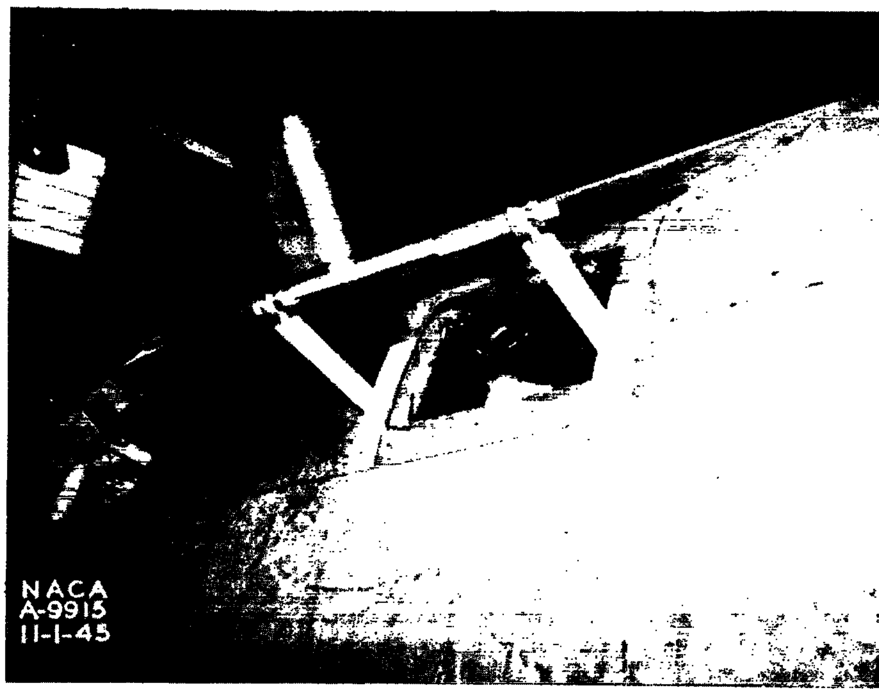

Figure 14.- Installation of mercury-in-glass thermometer on C-46 airplane.

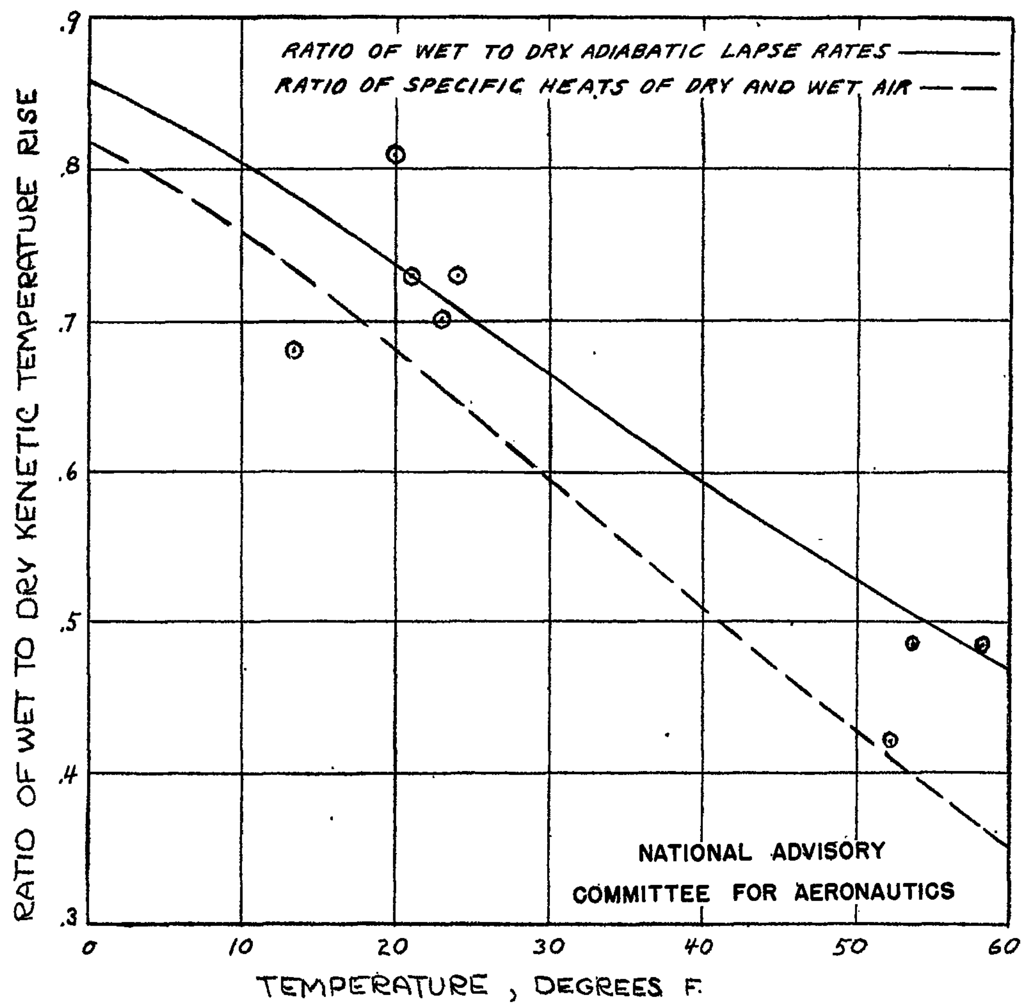

FIGURE 15.– RATIO OF WET TO DRY KENETIC TEMPERATURE RISE AS OBTAINED FROM OBSERVATIONS IN STRATUS CLOUDS. CURVES ARE FOR A PRESSURE ALTITUDE OF 2000 FEET WHICH IS THE APPROXIMATE AVERAGE ALTITUDE OF THE OBSERVATIONS.

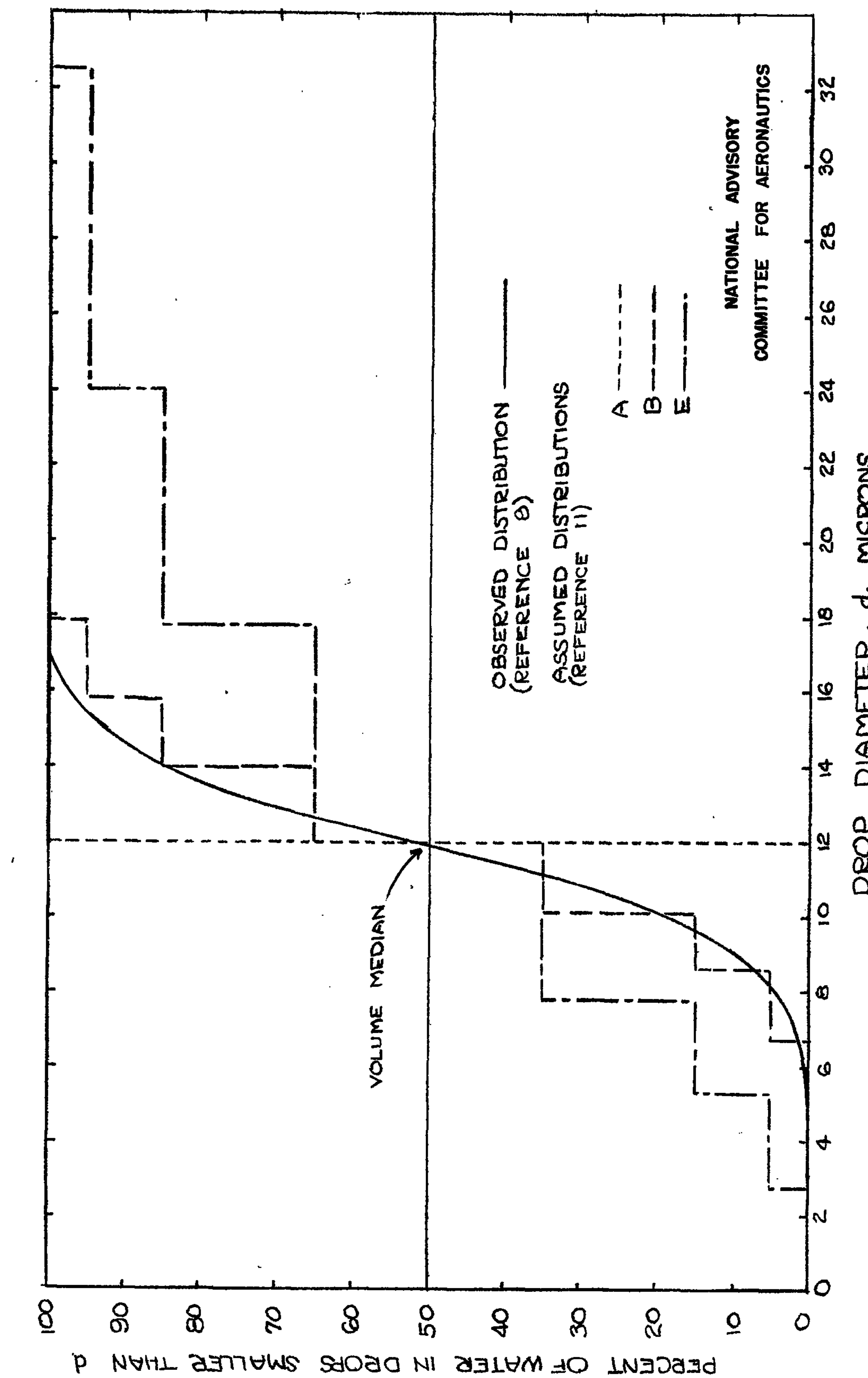

FIGURE 16.- VOLUME DISTRIBUTIONS OF DROP DIAMETER.